VERSION 1 CAPS

GRADE 10

PHYSICAL SCIENCE

WRITTEN BY VOLUNTEERS

EVERYTHING SCIENCE

Periodic Table of the Elements

No EN
Element
AMU

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VII	9 VII	10 VII	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 0
1 2.2 H 1,01																	2 He 4,00
3 0.98 Li 6,94	4 1.57 Be 9,01											5 2.04 B 10,8	6 2.55 C 12,0	7 3.04 N 14,0	8 3.44 O 16,0	9 3.98 F 19,0	10 Ne 20,2
11 0.93 Na 23,0	12 1.31 Mg 24,3											13 1.61 Al 27,0	14 1.90 Si 28,1	15 2.19 P 31,0	16 2.58 S 32,1	17 3.16 Cl 35,45	18 Ar 39,9
19 0.93 K 39,1	20 1.00 Ca 40,1	21 1.36 Sc 45,0	22 1.54 Ti 47,9	23 1.63 V 50,9	24 1.66 Cr 52,0	25 1.55 Mn 54,9	26 1.33 Fe 55,8	27 1.88 Co 58,9	28 1.91 Ni 58,7	29 1.90 Cu 63,5	30 1.65 Zn 65,4	31 1.81 Ga 69,7	32 2.01 Ge 72,6	33 2.18 As 74,9	34 2.55 Se 79,0	35 2.96 Br 79,9	36 Kr 83,8
37 0.82 Rb 85,5	38 0.95 Sr 87,6	39 1.22 Y 88,9	40 1.33 Zr 91,2	41 1.60 Nb 92,9	42 2.16 Mo 95,9	43 1.90 Tc (98)	44 2.20 Ru 101,1	45 2.28 Rh 102,9	46 2.20 Pd 106,4	47 1.93 Ag 107,9	48 1.69 Cd 112,4	49 1.78 In 114,8	50 1.96 Sn 118,7	51 2.05 Sb 121,8	52 2.10 Te 127,6	53 2.66 I 126,9	54 Xe 131,3
55 0.79 Cs 132,9	56 0.89 Ba 137,3	57-71 La-Lu Lanthanides	72 1.30 Hf 178,5	73 1.50 Ta 180,9	74 2.36 W 183,8	75 1.90 Re 186,2	76 2.20 Os 190,2	77 2.20 Ir 192,2	78 2.28 Pt 195,1	79 2.54 Au 197,0	80 2.00 Hg 200,6	81 1.62 Tl 204,4	82 2.33 Pb 207,2	83 2.02 Bi 209,0	84 2.00 Po (209)	85 2.20 At (210)	86 Rn (222)
87 0.7 Fr (223)	88 0.9 Ra 226,0	89-103 Ac-Lr Actinides	104 Rf (261)	105 Db (262)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (266)	110 Ds (269)	111 Rg (272)	112 Cn (277)	113 Uut (284)	114 Uuq (289)	115 Uup (288)	116 Uuh (293)	117 Uus (282)	118 Uuo (282)

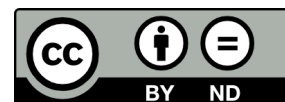
57 1.10 La 138,9	58 1.12 Ce 140,1	59 1.13 Pr 140,9	60 1.14 Nd 144,2	61 Pm (145)	62 1.17 Sm 150,4	63 Eu 152,0	64 1.20 Gd 157,3	65 Tb 158,9	66 1.22 Dy 162,5	67 1.23 Ho 164,9	68 1.24 Er 167,3	69 1.25 Tm 168,9	70 Yb 173,0	71 1.27 Lu 175,0
89 1.10 Ac 227,0	90 1.30 Th 232,0	91 1.50 Pa 231,0	92 1.38 U 238,0	93 1.36 Np 237,0	94 1.28 Pu (244)	95 1.30 Am (243)	96 1.30 Cm (247)	97 1.30 Bk (247)	98 1.30 Cf (251)	99 1.30 Es (252)	100 1.30 Fm (257)	101 1.30 Md (258)	102 1.30 No (258)	103 Lr (260)

- Transition Metal
- Metal
- Metalloid
- Non-metal
- Noble Gas
- Lanthanide
- Actinide

Everything Science

Grade 10 Physical Science

Version 1 – CAPS

by Siyavula and volunteers

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Everything Science

When we look outside at everything in nature, look around us at everything manufactured or look up at everything in space we cannot but be struck by the incredible diversity and complexity of life; so many things, that look so different, operating in such unique ways. The physical universe really contains incredible complexity.

Yet, what is even more remarkable than this seeming complexity is the fact that things in the physical universe are knowable. We can investigate them, analyse them and understand them. It is this ability to understand the physical universe that allows us to transform elements and make technological progress possible.

If we look back at some of the things that developed over the last century – space travel, advances in medicine, wireless communication (from television to mobile phones) and materials a thousand times stronger than steel – we see they are not the consequence of magic or some inexplicable phenomena. They were all developed through the study and systematic application of the physical sciences. So as we look forward at the 21st century and some of the problems of poverty, disease and pollution that face us, it is partly to the physical sciences we need to turn.

For however great these challenges seem, we know that the physical universe is knowable and that the dedicated study thereof can lead to the most remarkable advances. There can hardly be a more exciting challenge than laying bare the seeming complexity of the physical universe and working with the incredible diversity therein to develop products and services that add real quality to people's lives.

Physical sciences is far more wonderful, exciting and beautiful than magic! It is everywhere. See introductory video by Dr. Mark Horner: ▶ VPsfk at www.everythingscience.co.za

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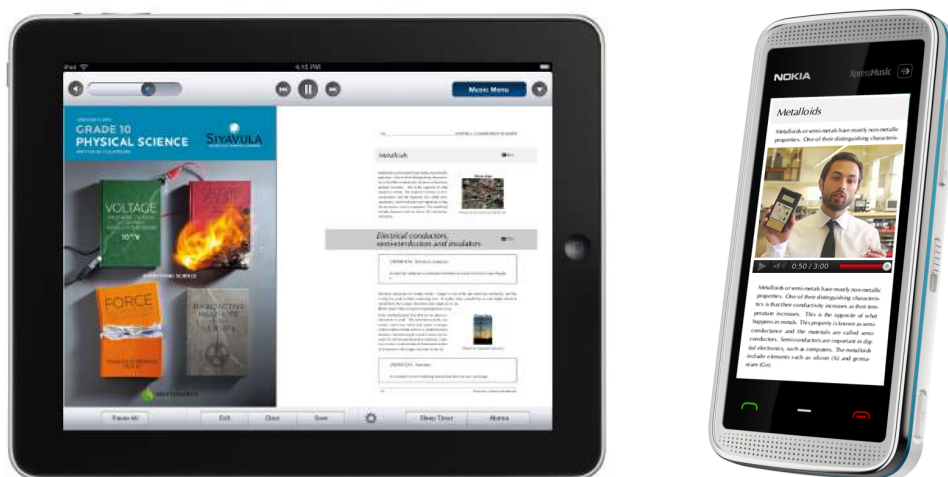
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(V123) Video, simulation or presentation

(P123) Practice and test your skills

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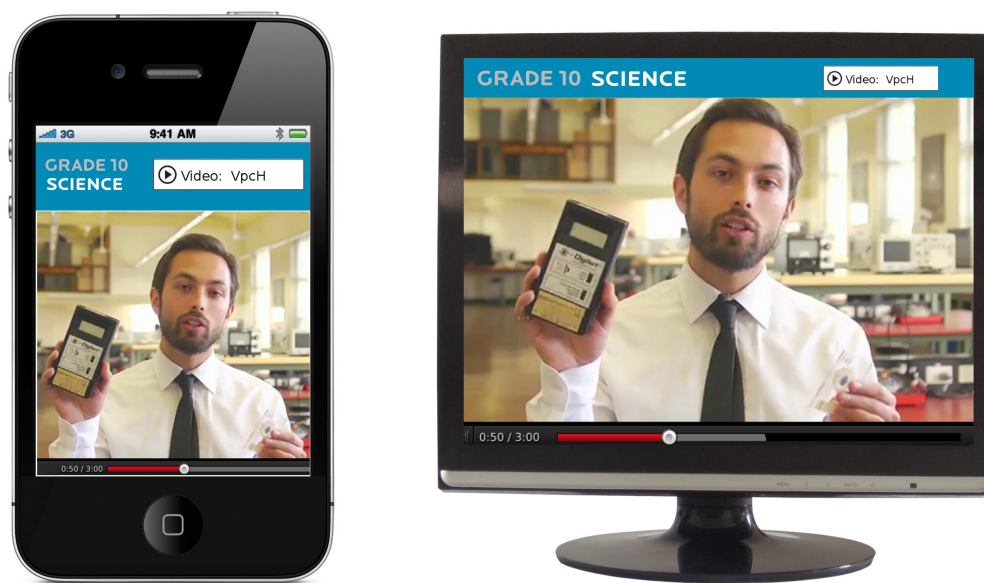
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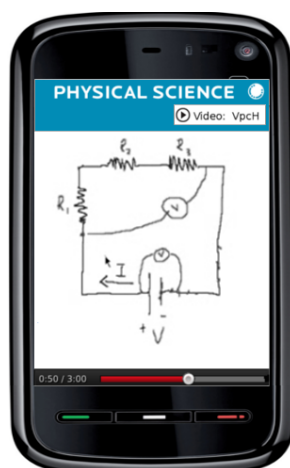
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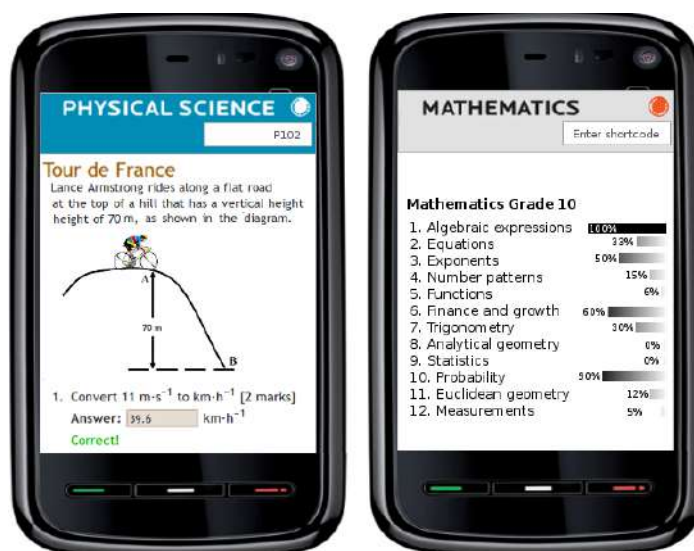
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(A123) Visit this section to post or view questions

(Q123) Questions or help with a specific question

Ask an expert

Can't find your question or the answer to it in the questions database? Then we invite you to try our service where you can send your question directly to an expert who will reply with an answer. Again, use the short-code for the section or exercise in the book to identify your problem area.

Contents

Skills for science 1

Introduction

 ESAA

In the physical sciences there are many skills that you need to learn. These include working with units, basic mathematics skills and laboratory skills. In this chapter we will revise some of these skills that you should know before starting to study physical science. This chapter is intended as a reference guide to assist you in your journey of studying physical science.

See introductory video: (Video: VPrny at www.everythingscience.co.za)

Mathematical skills

ESAB

You should be comfortable with scientific notation and how to write scientific notation. You should also be able to easily convert between different units and change the subject of a formula. In addition, concepts such as rate, direct and indirect proportion, fractions and ratios and the use of constants in equations are important.

Rounding off

 ESAC

Certain numbers may take an infinite amount of paper and ink to write out. Not only is that impossible, but writing numbers out to a high precision (many decimal places) is very inconvenient and rarely gives better answers. For this reason we often estimate the number to a certain number of decimal places.

Rounding off a decimal number to a given number of decimal places is the quickest way to approximate a number. For example, if you wanted to round-off $2,6525272$ to three decimal places then you would first count three places after the decimal. Next you mark this point with a $|$: $2,652|5272$. All numbers to the right of $|$ are ignored after you determine whether the number in the third decimal place must be rounded up or rounded down. You *round up* the final digit (make the digit one more) if the first digit after the $|$ is greater than

or equal to 5 and *round down* (leave the digit alone) otherwise. So, since the first digit after the | is a 5, we must round up the digit in the third decimal place to a 3 and the final answer of $2,6525272$ rounded to three decimal places is $2,653$.
In a calculation that has many steps, it is best to leave the rounding off right until the end. This ensures that your answer is more accurate.

Scientific notation

ESAD

In science one often needs to work with very large or very small numbers. These can be written more easily (and more compactly) in scientific notation, in the general form:

$$N \times 10^n$$

where N is a decimal number between 0 and 10 that is rounded off to a few decimal places. n is known as the *exponent* and is an integer. If $n > 0$ it represents how many times the decimal place in N should be moved to the right. If $n < 0$, then it represents how many times the decimal place in N should be moved to the left. For example $3,24 \times 10^3$ represents $3\ 240$ (the decimal moved three places to the right) and $3,24 \times 10^{-3}$ represents $0,00324$ (the decimal moved three places to the left).
If a number must be converted into scientific notation, we need to work out how many times the number must be multiplied or divided by 10 to make it into a number between 1 and 10 (i.e. the value of n) and what this number between 1 and 10 is (the value of N). We do this by counting the number of decimal places the decimal comma must move.
For example, write the speed of light ($299\ 792\ 458$ m $\cdot$ s^{-1}) in scientific notation, to two decimal places. First, we find where the decimal comma must go for two decimal places (to find N) and then count how many places there are after the decimal comma to determine n.
In this example, the decimal comma must go after the first 2, but since the number after the 9 is 7, $N = 3,00$. $n = 8$ because there are 8 digits left after the decimal comma. So the speed of light in scientific notation, to two decimal places is $3,00 \times 10^8$ m $\cdot$ s^{-1}.
We can also perform addition, subtraction, multiplication and division with scientific notation. The following two worked examples show how to do this:

Example 1: *Addition and subtraction with scientific notation*

QUESTION

$1,99 \times 10^{-26} + 1,67 \times 10^{-27} - 2,79 \times 10^{-25} = ?$

SOLUTION

Step 1 : ***Make all the exponents the same***

To add or subtract numbers in scientific notation we must make all the exponents the same:

$1,99 \times 10^{-26} = 0,199 \times 10^{-25}$ and

$1,67 \times 10^{-27} = 0,0167 \times 10^{-25}$

Step 2 : ***Carry out the addition and subtraction***

Now that the exponents are the same we can simply add or subtract the N part of each number:

$0,199 + 0,0167 - 2,79 = -2,5743$

Step 3 : ***Write the final answer***

To get the final answer we put the common exponent back:

$-2,5743 \times 10^{-25}$

Note that we follow the same process if the exponents are positive. For example $5,1 \times 10^{3} + 4,2 \times 10^{4} = 4,71 \times 10^{4}$.

Example 2: *Multiplication and division with scientific notation*

QUESTION

$1,6 \times 10^{-19} \times 3,2 \times 10^{-19} \div 5 \times 10^{-21}$

SOLUTION

Step 1 : ***Carry out the multiplication***

For multiplication and division the exponents do not need to be the same. For multiplication we add the exponents and multiply the N terms:

$1,6 \times 10^{-19} \times 3,2 \times 10^{-19} = (1,6 \times 3,2) \times 10^{-19+(-19)} = 5,12 \times 10^{-38}$

Step 2 : ***Carry out the division***

For division we subtract the exponents and divide the N terms. Using our result from the previous step we get:
$2,56 \times 10^{-38} \div 5 \times 10^{-21} = (5,12 \div 5) \times 10^{-38-(-19)} = 1,024 \times 10^{-18}$

Step 3 : ***Write the final answer***

The answer is: $1,024 \times 10^{-18}$

Note that we follow the same process if the exponents are positive. For example: $5,1 \times 10^3 \times 4,2 \times 10^4 = 21,42 \times 10^7 = 2,142 \times 10^8$

Units

ESAE

Imagine you had to make curtains and needed to buy fabric. The shop assistant would need to know how much fabric you needed. Telling her you need fabric 2 wide and 6 long would be insufficient — you have to specify the **unit** (i.e. 2 *metres* wide and 6 *metres* long). Without the unit the information is incomplete and the shop assistant would have to guess. If you were making curtains for a doll's house the dimensions might be 2 centimetres wide and 6 centimetres long!
It is not just lengths that have units, all physical quantities have units (e.g. time, temperature, distance, etc.).

DEFINITION: Physical Quantity

A physical quantity is anything that you can measure. For example, length, temperature, distance and time are physical quantities.

There are many different systems of units. The main systems of units are:

- SI units
- c.g.s units
- Imperial units
- Natural units

SI Units ESAF

We will be using the SI units in this course. SI units are the internationally agreed upon units.

> **DEFINITION: SI Units**
>
> The name *SI units* comes from the French *Système International d'Unités*, which means *international system of units*.

There are seven base SI units. These are listed in table 1.1. All physical quantities have units which can be built from these seven base units. So, it is possible to create a different set of units by defining a different set of base units.
These seven units are called base units because none of them can be expressed as combinations of the other six. These base units are like the 26 letters of the alphabet for English. Many different words can be formed by using these letters.

Base quantity	**Name**	**Symbol**
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

Table 1.1: SI Base Units

The Other Systems of Units ESAG

The SI Units are not the only units available, but they are most widely used. In Science there are three other sets of units that can also be used. These are mentioned here for

interest only.

- **c.g.s. Units**
  In the c.g.s. system, the metre is replaced by the centimetre and the kilogram is replaced by the gram. This is a simple change but it means that all units derived from these two are changed. For example, the units of force and work are different. These units are used most often in astrophysics and atomic physics.

- **Imperial Units**
  Imperial units arose when kings and queens decided the measures that were to be used in the land. All the imperial base units, except for the measure of time, are different to those of SI units. This is the unit system you are most likely to encounter if SI units are not used. Examples of imperial units are pounds, miles, gallons and yards. These units are used by the Americans and British. As you can imagine, having different units in use from place to place makes scientific communication very difficult. This was the motivation for adopting a set of internationally agreed upon units.

- **Natural Units**
  This is the most sophisticated choice of units. Here the most fundamental discovered quantities (such as the speed of light) are set equal to 1. The argument for this choice is that all other quantities should be built from these fundamental units. This system of units is used in high energy physics and quantum mechanics.

Combinations of SI base units www *ESAH*

To make working with units easier, some combinations of the base units are given special names, but it is always correct to reduce everything to the base units. Table 1.2 lists some examples of combinations of SI base units that are assigned special names. Do not be concerned if the formulae look unfamiliar at this stage - we will deal with each in detail in the chapters ahead (as well as many others)!

It is very important that you are able to recognise the units correctly. For example, the **newton** (N) is another name for the **kilogram metre per second squared** ($kg{\cdot}m{\cdot}s^{-2}$), while the **kilogram metre squared per second squared** ($kg{\cdot}m^2{\cdot}s^{-2}$) is called the **joule** (J).

Quantity	**Formula**	**Unit Expressed in Base Units**	**Name of Combination**
Force	ma	kg · m · s^{-2}	N (newton)
Frequency	$\frac{1}{T}$	s^{-1}	Hz (hertz)
Work	Fs	kg · m^2 · s^{-2}	J (joule)

Table 1.2: Some examples of combinations of SI base units assigned special names

Prefixes of base units

ESAI

Tip

When writing combinations of base SI units, place a dot (·) between the units to indicate that different base units are used. For example, the symbol for metres per second is correctly written as m·s^{-1}, and not as ms^{-1} or m/s. Although the last two options will be accepted in tests and exams, we will only use the first one in this book.

Now that you know how to write numbers in scientific notation, another important aspect of units is the prefixes that are used with the units. In the case of units, the prefixes have a special use. The kilogram (kg) is a simple example. 1 kg is equal to 1 000 g or 1×10^3 g. Grouping the 10^3 and the g together we can replace the 10^3 with the prefix k (kilo). Therefore the k takes the place of the 10^3. The kilogram is unique in that it is the only SI base unit containing a prefix.

In science, all the prefixes used with units are some power of 10. Table 1.3 lists some of these prefixes. You will not use most of these prefixes, but those prefixes listed in **bold** should be learnt. The case of the prefix symbol is very important. Where a letter features twice in the table, it is written in uppercase for exponents bigger than one and in lowercase for exponents less than one. For example M means mega (10^6) and m means milli (10^{-3}).

Prefix	**Symbol**	**Exponent**	**Prefix**	**Symbol**	**Exponent**
yotta	Y	10^{24}	yocto	y	10^{-24}
zetta	Z	10^{21}	zepto	z	10^{-21}
exa	E	10^{18}	atto	a	10^{-18}
peta	P	10^{15}	femto	f	10^{-15}
tera	T	10^{12}	pico	p	10^{-12}
giga	G	10^{9}	**nano**	n	10^{-9}
mega	M	10^{6}	**micro**	μ	10^{-6}
kilo	k	10^{3}	**milli**	m	10^{-3}
hecto	h	10^{2}	**centi**	c	10^{-2}
deca	da	10^{1}	**deci**	d	10^{-1}

Table 1.3: Unit Prefixes

Tip

There is no space and no dot between the prefix and the symbol for the unit.

Here are some examples of the use of prefixes:

- $40\ 000$ m can be written as 40 km (kilometre)
- $0,001$ g is the same as 1×10^{-3} g and can be written as 1 mg (milligram)
- $2,5 \times 10^{6}$ N can be written as $2,5$ MN (meganewton)
- $250\ 000$ A can be written as 250 kA (kiloampere) or $0,250$ MA (megaampere)
- $0,000000075$ s can be written as 75 ns (nanoseconds)
- 3×10^{-7} mol can be rewritten as $0,3 \times 10^{-6}$ mol, which is the same as $0,3$ μmol (micromol)

Exercise 1 - 1

1. Carry out the following calculations:
   a. $1,63 \times 10^{5} + 4,32 \times 10^{6} - 8,53 \times 10^{5}$
   b. $7,43 \times 10^{3} \div 6,54 \times 10^{7} \times 3,33 \times 10^{5}$
   c. $6,21434534 \times 10^{-5} \times 3,2555 \times 10^{-3} + 6,3 \times 10^{-4}$
2. Write the following in scientific notation using Table 1.3 as a reference.
   a. $0,511$ MV
   b. 10 cℓ
   c. $0,5$ μm

d. 250 nm
e. $0,00035$ hg

3. Write the following using the prefixes in Table 1.3.
   a. $1,602 \times 10^{-19}$ C
   b. $1,992 \times 10^{6}$ J
   c. $5,98 \times 10^{4}$ N
   d. 25×10^{-4} A
   e. $0,0075 \times 10^{6}$ m

More practice video solutions or help at www.everythingscience.co.za

(1.) 02u4 (2.) 01v7 (3.) 01v8

The Importance of Units ESAJ

Without units much of our work as scientists would be meaningless. We need to express our thoughts clearly and units give meaning to the numbers we measure and calculate. Depending on which units we use, the numbers are different. For example if you have 12 water, it means nothing. You could have 12 ml of water, 12 litres of water, or even 12 bottles of water. Units are an essential part of the language we use. Units must be specified when expressing physical quantities. Imagine that you are baking a cake, but the units, like grams and millilitres, for the flour, milk, sugar and baking powder are not specified!

Group Discussion: Importance of Units

Work in groups of 5 to discuss other possible situations where using the incorrect set of units can be to your disadvantage or even dangerous. Look for examples at home, at school, at a hospital, when travelling and in a shop.

Case Study: The importance of units

Read the following extract from CNN News 30 September 1999 and answer the questions below.

NASA: Human error caused loss of Mars orbiter November 10, 1999

Failure to convert English measures to metric values caused the loss of the Mars Climate Orbiter, a spacecraft that smashed into the planet instead of reaching a safe orbit, a NASA investigation concluded Wednesday.

The Mars Climate Orbiter, a key craft in the space agency's exploration of the red planet, vanished on 23 September after a 10 month journey. It is believed that the craft came dangerously close to the atmosphere of Mars, where it presumably burned and broke into pieces.
An investigation board concluded that NASA engineers failed to convert English measures of rocket thrusts to newton, a metric system measuring rocket force. One English pound of force equals 4,45 newtons. A small difference between the two values caused the spacecraft to approach Mars at too low an altitude and the craft is thought to have smashed into the planet's atmosphere and was destroyed.
The spacecraft was to be a key part of the exploration of the planet. From its station about the red planet, the Mars Climate Orbiter was to relay signals from the Mars Polar Lander, which is scheduled to touch down on Mars next month.
"The root cause of the loss of the spacecraft was a failed translation of English units into metric units and a segment of ground-based, navigation-related mission software," said Arthur Stephenson, chairman of the investigation board.
Questions:

1. Why did the Mars Climate Orbiter crash? Answer in your own words.
2. How could this have been avoided?
3. Why was the Mars Orbiter sent to Mars?
4. Do you think space exploration is important? Explain your answer.

How to change units

ESAK

It is very important that you are aware that different systems of units exist. Furthermore, you must be able to convert between units. Being able to change between units (for example, converting from millimetres to metres) is a useful skill in Science.
The following conversion diagrams will help you change from one unit to another.

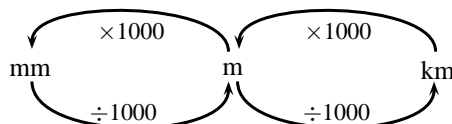



Figure 1.2: The distance conversion table

If you want to change millimetre to metre, you divide by 1000 (follow the arrow from mm to m); or if you want to change kilometre to millimetre, you multiply by 1000×1000.

The same method can be used to change millilitre to litre or kilolitre. Use Figure 1.3 to

change volumes:

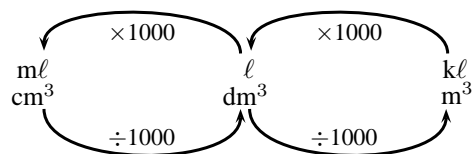



Figure 1.3: The volume conversion table

Example 3: *Conversion 1*

QUESTION

Express 3 800 mm in metres.

SOLUTION

Step 1 : ***Use the conversion table***
Use Figure 1.2. Millimetre is on the left and metre in the middle.

Step 2 : ***Decide which direction you are moving***
You need to go from mm to m, so you are moving from left to right.

Step 3 : ***Write the answer***
$3800 \text{ mm} \div 1\ 000 = 3,8 \text{ m}$

Example 4: *Conversion 2*

QUESTION

Convert 4,56 kg to g.

SOLUTION

Step 1 : ***Find the two units on the conversion diagram.***
Use Figure 1.2. Kilogram is the same as kilometre and gram is the same as metre.

Step 2 : ***Decide whether you are moving to the left or to the right.***
You need to go from kg to g, so it is from right to left.

Step 3 : ***Read from the diagram what you must do and find the answer.***
$4,56 \text{ kg} \times 1\ 000 = 4\ 560 \text{ g}$

Two other useful conversions

Very often in science you need to convert speed and temperature. The following two rules will help you do this:

1. **Converting speed**
   When converting km · h^{-1} to m · s^{-1} you multiply by $1\ 000$ and divide by $3\ 600$ ($\frac{1000 \text{ m}}{3600 \text{ s}}$). For example 72 km · h^{-1} $\div 3,6 = 20$m · s^{-1}.
   When converting m · s^{-1} to km · h^{-1}, you multiply by $3\ 600$ and divide by $1\ 000$ ($\frac{3600 \text{ s}}{1000 \text{ m}}$). For example 30 m · s^{-1} $\times 3,6 = 108$km · h^{-1}.
2. **Converting temperature**
   Converting between the Kelvin and Celsius temperature scales is simple. To convert from Celsius to Kelvin add 273. To convert from Kelvin to Celsius subtract 273. Representing the Kelvin temperature by T_K and the Celsius temperature by $T_{^\circ C}$:

$$T_K = T_{^\circ C} + 273$$

Changing the subject of a formula

ESAL

Very often in science you will have to change the subject of a formula. We will look at two examples. (Do not worry if you do not yet know what the terms and symbols mean, these formulae will be covered later in the book.)

1. **Moles**
   The equation to calculate moles from molar mass is: $n = \frac{m}{M}$, where n is the number of moles, m is the mass and M is the molar mass. As it is written we can easily find the number of moles of a substance. But what if we have the number of moles and want to find the molar mass? We note that we can simply multiply both sides of the equation by the molar mass and then divide both sides by the number of moles:

$$\begin{aligned} n &= \frac{m}{M} \\ nM &= m \\ M &= \frac{m}{n} \end{aligned}$$

   And if we wanted the mass we would use: $m = nM$.

2. Energy of a photon
   The equation for the energy of a photon is $E = h\frac{c}{\lambda}$, where E is the energy, h is Planck's constant, c is the speed of light and λ is the wavelength. To get c we can do the following:

$$\begin{aligned} E &= h\frac{c}{\lambda} \\ E\lambda &= hc \\ c &= \frac{E\lambda}{h} \end{aligned}$$

   Similarly we can find the wavelength we use: $\lambda = \frac{hc}{E}$ and to find Planck's constant we use: $h = \frac{E\lambda}{c}$.

Rate, proportion and ratios

ESAM

In science we often want to know how a quantity relates to another quantity or how something changes over a period of time. To do this we need to know about rate, proportion and ratios.

Rate:

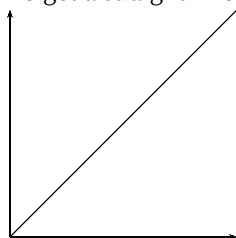
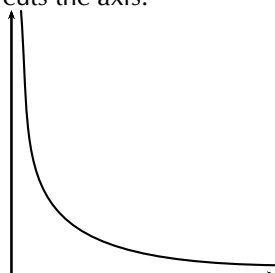
The rate at which something happens is the number of times that it happens over a period of time. The rate is always a change per time unit. So we can get rate of change of velocity per unit time ($\frac{\Delta \vec{v}}{t}$) or the rate of change in concentration per unit time (or $\frac{\Delta C}{t}$). (Note that Δ represents a change in).

Ratios and fractions:

A fraction is a number which represents a part of a whole and is written as $\frac{a}{b}$, where a is the numerator and b is the denominator. A ratio tells us the relative size of one quantity (e.g. number of moles of reactants) compared to another quantity (e.g. number of moles of product): $2:1$, $4:3$, etc. Ratios can also be written as fractions as percentages (fractions with a denominator of 100).

Proportion:

Proportion is a way of describing relationships between values or between constants. We can say that x is directly proportional to y ($x \propto y$) or that a is inversely proportional to b ($a \propto \frac{1}{b}$). It is important to understand the difference between directly and inversely proportional.

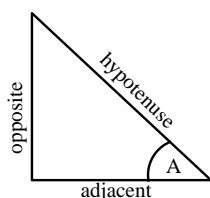
- **Directly proportional**
  Two values or constants are directly proportional when a change in one leads to the same change in the other. This is a more-more relationship. We can represent this as $y \propto x$ or $y = kx$ where k is the proportionality constant. We have to include k since we do not know by how much x changes when y changes. x could change by 2 for every change of 1 in y. If we plot two directly proportional variables on a graph, then we get a straight line graph that goes through the origin $(0;0)$:

- **Inversely proportional**
  Two values or constants are inversely proportional when a change in one leads to the opposite change in the other. We can represent this as $y = \frac{k}{x}$. This is a more-less relationship. If we plot two inversely proportional variables we get a curve that never cuts the axis:

Constants in equations ESAN

A constant in an equation **always** has the same value. For example the speed of light ($c = 2,99 \times 10^8$ m$\cdot$ s^{-1}), Planck's constant (h) and Avogadro's number (N_A) are all examples of constants that are use in science. The following table lists all the constants that you will encounter in this book.

Constant	Symbol	**Value and units**	**SI Units**
Atomic mass unit	u	$1,67 \times 10^{-24}$ g	$1,67 \times 10^{-27}$ kg
Charge on an electron	e	$-1,6 \times 10^{-19}$ C	$-1,6 \times 10^{-19}$ s $\cdot$ A
Speed of sound (in air, at 25°)		$344 m \cdot s^{-1}$	
Speed of light	c	$3 \times 10^8 m \cdot s^{-1}$	
Planck's constant	h	$6,626 \times 10^{-34}$ J $\cdot$ s	$6,626 \times 10^{-34}$ kg $\cdot$ m^{2}s^{-1}
Avogadro's number	N_A	$6,022 \times 10^{23}$	
Gravitational acceleration	g	$9,8$ m $\cdot$ s^{-1}	

Trigonometry ESAO

Trigonometry is the relationship between the angles and sides of right angled triangles. Trigonometrical relationships are ratios and therefore have no units. You should know the following trigonometric ratios:

- Sine
  This is defined as sin$A = \frac{\text{opposite}}{\text{hypotenuse}}$
- Cosine
  This is defined as cos$A = \frac{\text{adjacent}}{\text{hypotenuse}}$

- Tangent
  This is defined as $\tan A = \frac{\text{opposite}}{\text{adjacent}}$

Exercise 1 - 2

1. Write the following quantities in scientific notation:
   a. 10130 Pa to 2 decimal places
   b. 978,15 m·s^{-2} to one decimal place
   c. 0,000001256 A to 3 decimal places
2. For each of the following symbols, write out the unit in full and write what power of 10 it represents:
   a. μg
   b. mg
   c. kg
   d. Mg
3. Write each of the following in scientific notation, correct to 2 decimal places:
   a. 0,00000123 N
   b. 417 000 000 kg
   c. 246800 A
   d. 0,00088 mm
4. For each of the following, write the measurement using the correct symbol for the prefix and the base unit:
   a. 1,01 microseconds
   b. 1 000 milligrams
   c. 7,2 megametres
   d. 11 nanolitre
5. The Concorde is a type of aeroplane that flies very fast. The top speed of the Concorde is 844 km·hr^{-1}. Convert the Concorde's top speed to m·s^{-1}.
6. The boiling point of water is 100 °C. What is the boiling point of water in kelvin?

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(1.) 01v9 (2.) 01va (3.) 01vb (4.) 01vc (5.) 01vd (6.) 01ve

Skills in the laboratory

ESAP

To carry out experiments in the laboratory you need to know how to properly present your experimental results, you also need to know how to read instruments and how to interpret your data. A laboratory (be it for physics, chemistry or other sciences) can be a very dangerous and daunting place. However, if you follow a few simple guidelines you can safely carry out experiments in the laboratory without endangering yourself or others around you.

Experiments

ESAQ

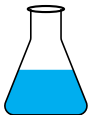
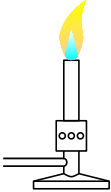
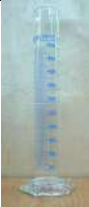
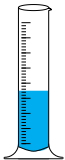
When a scientist performs experiments the following process is followed:

- Observe an event and identify an answerable question about the event.
- Make a hypothesis (theory) about the event that gives a sensible result.
- Design an experiment to test the theory. This includes identifying the fixed factors (what will not vary in the experiment), identifying the independent variable (this is set) and the dependent variable (what you will actually measure).
- Collect data accurately and interpret the data.
- Draw conclusions from the results of the experiment.
- Decide whether the hypothesis is correct or not.
- Verify your results by repeating the experiment or getting someone else to repeat the experiment.

This process is known as the scientific method. In the work that you will do you will be given the first three items and be required to determine the last four items. For verifying results you should see what your classmates obtained for their experiment.
In science the recording of practical work follows a specific layout. You should always present your work using this layout, as it will help any other person be able to understand and repeat your experiment.

- Aim: A brief sentence describing the purpose of the experiment.
- Apparatus: A sketch of the apparatus and a list of the apparatus

- Method: A list of the steps followed to carry out the experiment
- Results: Tables, graphs and observations about the experiment
- Discussion: What your results mean
- Conclusion: A brief sentence concluding whether or not the aim was met

To perform experiments correctly and accurately you also need to know how to work with various pieces of equipment. The next section details some of the apparatus that you need to know, as well as how to correctly work with it.

As you work through the experiments in the book you will be given guidance on how to present your data. By the end of the year you should be able to select the appropriate method to show your data, whether it is a table, a graph or an equation.

You will also need to know how to interpret your data. For example given a table of values, what can you say about those values. Also you should be able to say whether you are performing a qualitative (descriptive) or a quantitative (numbers) analysis.

Laboratory apparatus www *ESAR*

Listed here are some of the common pieces of apparatus that you will be working with in the laboratory. You should be able to name all the apparatus listed here as well as make a simple sketch of it.

Item	Photo	Sketch
Beaker		
Flask		
Test tubes		
Bunsen burner		
Measuring cylinder		
Pipette		
Watch glass		
Thermometer		
Funnel		

The following image shows the correct setup for heating liquids on a Bunsen burner:

When reading any instrument (such as a measuring cylinder, a pipette, etc.) always make sure that the instrument is level and that your eye is at the level of the top of the liquid.

General safety rules ESAS

The following are some of the general guidelines and rules that you should always observe when working in a laboratory.

1. You are responsible for your own safety as well as the safety of others in the laboratory.
2. Do not eat or drink in the laboratory. Do not use laboratory glassware to eat or drink from.
3. Always behave responsibly in the laboratory. Do not run around or play practical jokes.
4. In case of accidents or chemical spills call your teacher at once.
5. Always check with your teacher how to dispose of waste. Chemicals should not be disposed of down the sink.
6. Only perform the experiments that your teacher instructs you to. Never mix chemicals for fun.
7. Never perform experiments alone.
8. Always check the safety data of any chemicals you are going to use.
9. Follow the given instructions exactly. Do not mix up steps or try things in a different order.
10. Be alert and careful when handling chemicals, hot glassware, etc.
11. Ensure all Bunsen burners are turned off at the end of the practical and all chemical containers are sealed.
12. Never add water to acid. Always add the acid to water.
13. Never heat thick glassware as it will break. (i.e. do not heat measuring cylinders).
14. When you are smelling chemicals, place the container on a laboratory bench and

use your hand to gently waft (fan) the vapours towards you.

15. Do not take chemicals from the laboratory.
16. Always work in a well ventilated room. Whenever you perform experiments, you should open the windows.
17. Do not leave Bunsen burners and flames unattended.
18. Never smell, taste or touch chemicals unless instructed to do so.
19. Never point test tubes at people or yourself. When heating chemicals, always point the mouth of the test tube away from you and your classmates.

Hazard signs

The table below lists some of the common hazards signs that you may encounter. You should know what all of these mean.

Sign	Symbol	Meaning	Sign	Symbol	Meaning
	C	Corrosive. Chemicals with this label can burn your skin and eyes and burn holes in your clothes. An example is hydrochloric acid.		N	Environmentally harmful. Chemicals with this label are damaging to the environment. An example is CFC's.

continued on next page

Sign	Symbol	Meaning	Sign	Symbol	Meaning
	E	Explosive. Chemicals with this label explode easily. An example is lead azide.		F	Flammable. Chemicals with this label can catch fire easily. Example: methanol
	Xn	Harmful. Chemicals labelled with this are generally considered to be damaging to humans.		Xi	Irritant. Chemicals with this label cause irritation to your eyes and skin. An example is hydrogen peroxide.
	O	Oxidising. Chemicals with this label contain oxygen that may cause other materials to combust. An example is potassium dichromate.		T	Toxic. Chemicals with this label are highly toxic. An example is mercury.

Notes and information

ESAU

You can find safety data sheets at *http://www.msds.com/*. You should always look at these data sheets anytime you work with a new chemical. These data sheets contain information about how to work with chemicals and what dangers the chemicals pose to you and the environment. You should always try dispose of chemicals correctly and safely. Many chemicals cannot simply be washed down the sink.

Classification of matter 2

Materials

 ESAV

All the objects that we see in the world around us, are made of **matter**. Matter makes up the air we breathe, the ground we walk on, the food we eat and the animals and plants that live around us. Even our own human bodies are made of matter!

Different objects can be made of different types of **materials** (the matter from which objects are made). For example, a cupboard (an *object*) is made of wood, nails, hinges and knobs (the *materials*). The **properties** of the materials will affect the properties of the object. In the example of the cupboard, the strength of the wood and metals make the cupboard strong and durable. It is very important to understand the properties of materials, so that we can use them in our homes, in industry and in other applications.

Cupboard

Photo by grongar on Flickr.com

See introductory video: (Video: VPabo at www.everythingscience.co.za)

Some of the properties of matter that you should know are:

- Materials can be **strong** and resist bending (e.g. bricks, rocks) or **weak** and bend easily (e.g. clothes)
- Materials that conduct heat (e.g. metals) are called **thermal conductors**. Materials that conduct electricity (e.g. copper wire) are **electrical conductors**.
- **Brittle** materials break easily (e.g. plastic). Materials that are **malleable** can be easily formed into different shapes (e.g. clay, dough). **Ductile** materials are able to be formed into long wires (e.g. copper).
- **Magnetic** materials have a magnetic field (e.g. iron).
- **Density** is the mass per unit volume. Examples of dense materials include concrete and stones.
- The **boiling and melting points** of substances tells us the temperature at which the substance will boil or melt. This helps us to classify substances as solids, liquids or gases at a specific temperature.

The diagram below shows one way in which matter can be classified (grouped) according

to its different properties. As you read further in this chapter, you will see that there are also other ways of classifying materials, for example according to whether or not they are good electrical conductors.

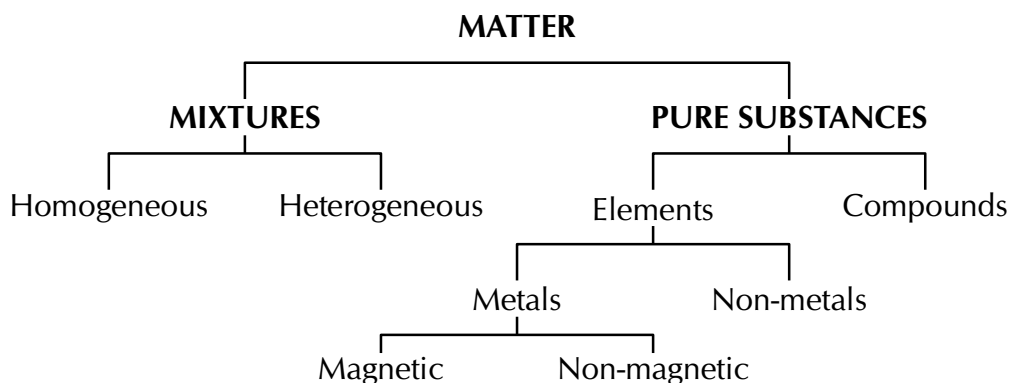



Figure 2.2: The classification of matter

Activity:	*What materials are products made of?*

This activity looks at the materials that make up food products. In groups of 3 or 4 look at the labels on food items. Make a list of the ingredients. Can you tell from the ingredients what the food is (i.e. spice, oil, sweets, etc.)? Food products are labelled to help you (the consumer) know what you are eating and to help you choose healthier alternatives. Some compounds, such as MSG and tartrazine are being removed from products due to being regarded as unsafe. Are there other ingredients in the products that are unsafe to eat? What preservatives and additives (e.g. tartrazine, MSG, colourants) are there? Are these preservatives and additives good for you? Are there natural (from plants) alternatives? What do different indigenous people groups use to flavor and preserve their food?

Some labels on food items

Activity: *Classifying materials*

Look around you at the various structures. Make a list of all the different materials that you see. Try to work out why a particular material was used. Can you classify all the different materials used according to their properties? Why are these materials chosen over other materials?

Picture by flowcomm on Flickr.com

Mixtures

ESAW

We see mixtures all the time in our everyday lives. A stew, for example, is a mixture of different foods such as meat and vegetables; sea water is a mixture of water, salt and other substances, and air is a mixture of gases such as carbon dioxide, oxygen and nitrogen.

> *DEFINITION: Mixture*
>
> A mixture is a combination of two or more substances, where these substances are not bonded (or joined) to each other and no chemical reaction occurs between the substances.

In a mixture, the substances that make up the mixture:

- **are not in a fixed ratio**
  Imagine, for example, that you have 250 ml of water and you add sand to the water. It doesn't matter whether you add 20 g, 40 g, 100 g or any other mass of sand to the water; it will still be called a mixture of sand and water.
- **keep their physical properties**
  In the example we used of sand and water, neither of these substances has changed in any way when they are mixed together. The sand is still sand and the water is still water.
- **can be separated by mechanical means**
  To separate something by "mechanical means", means that there is no chemical process involved. In our sand and water example, it is possible to separate the mixture by

simply pouring the water through a filter. Something *physical* is done to the mixture, rather than something *chemical*.

We can group mixtures further by dividing them into those that are heterogeneous and those that are homogeneous.

Heterogeneous mixtures ESAX

A **heterogeneous** mixture does not have a definite composition. Cereal in milk is an example of a heterogeneous mixture. Soil is another example. Soil has pebbles, plant matter and sand in it. Although you may add one substance to the other, they will stay separate in the mixture. We say that these heterogeneous mixtures are *non-uniform*, in other words they are not exactly the same throughout.

Cereal

Picture by dougww on Flickr.com

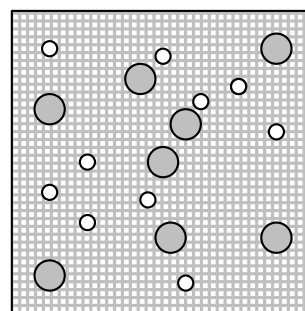



Figure 2.3: A submicroscopic representation of a heterogeneous mixture. The gray circles are one substance (e.g. one cereal) and the white circles are another substance (e.g. another cereal). The background is the milk.

> *DEFINITION: Heterogeneous mixture*
>
> A heterogeneous mixture is one that consists of two or more substances. It is non-uniform and the different components of the mixture can be seen.

Heterogeneous mixtures can be further subdivided according to whether it is two liquids mixed, a solid and a liquid or a liquid and a gas or even a gas and a solid. These mixtures are given special names which you can see in table below.

Phases of matter	Name of mixture	Example
liquid-liquid	emulsion	oil in water
solid-liquid	suspension	muddy water
gas-liquid	aerosol	fizzy drinks
gas-solid	smoke	smog

Table 2.1: Examples of different heterogeneous mixtures

Homogeneous mixtures

ESAY

A **homogeneous** mixture has a definite composition, and specific properties. In a homogeneous mixture, the different parts cannot be seen. A solution of salt dissolved in water is an example of a homogeneous mixture. When the salt dissolves, it spreads evenly through the water so that all parts of the solution are the same, and you can no longer see the salt as being separate from the water. Think also of coffee without milk. The air we breathe is another example of a homogeneous mixture since it is made up of different gases which are in a constant ratio, and which can't be visually distinguished from each other (i.e. you can't see the different components).

See video: VPabz at www.everythingscience.co.za

Coffee

Photo by Julius Schorzman on Wikimedia

Salt dissolving in water

> **DEFINITION: Homogeneous mixture**
>
> A homogeneous mixture is one that is uniform, and where the different components of the mixture cannot be seen.

FACT

An **alloy** is a homogeneous mixture of two or more elements, at least one of which is a metal, where the resulting material has metallic properties. For example steel is an alloy made up mainly from iron with a small amount of carbon (to make it harder), manganese (to make it strong) and chromium (to prevent rusting).

Example 1: *Mixtures*

QUESTION

For each of the following mixtures state whether it is a homogeneous or a heterogeneous mixture:

a. *sugar dissolved in water*
b. *flour and iron filings (small pieces of iron)*

SOLUTION

Step 1 : ***Look at the definition***

We first look at the definition of a heterogeneous and homogeneous mixture.

Step 2 : ***Decide whether or not you can see the components***

a. We cannot see the sugar in the water.
b. We are able to make out the pieces of iron in the flour.

Step 3 : ***Decide whether or not the components are mixed uniformly***

a. The two components are mixed uniformly.
b. In this mixture there may be places where there are a lot of iron filings and places where there is more flour, so it is not uniformly mixed.

Step 4 : ***Give the final answer***

a. Homogeneous mixture.
b. Heterogeneous mixture.

Activity: *Making mixtures*

Make mixtures of sand and water, potassium dichromate and water, iodine and ethanol, iodine and water. Classify these as heterogeneous or homogeneous. Give reasons for your choice.

Make your own mixtures by choosing any two substances from

- sand
- water
- stones
- cereal
- salt
- sugar

Try to make as many different mixtures as possible. Classify each mixture and give a reason for your choice.

Potassium dichromate (top) and iodine (bottom)

Exercise 2 - 1

Complete the following table:

Substance	Non-mixture or mixture	Heterogeneous mixture	Homogeneous mixture
tap water			
brass (an alloy of copper and zinc)			
concrete			
aluminium foil (tinfoil)			
Coca Cola			
soapy water			
black tea			
sugar water			
baby milk formula			

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(1.) 0000

Pure substances

ESAZ

Any material that is not a mixture, is called a **pure substance**. Pure substances include **elements** and **compounds**. It is much more difficult to break down pure substances into their parts, and complex chemical methods are needed to do this.

See video: VPacc at www.everythingscience.co.za

We can use melting and boiling points and chromatography to test for pure substances. Pure substances have a sharply defined (one temperature) melting or boiling point. Impure substances have a temperature range over which they melt or boil. Chromatography is the process of separating substances into their individual components. If a substance is pure then chromatography will only produce one substance at the end of the process. If a substance is impure then several substances will be seen at the end of the process.

Activity: *Recommended practical activity: Smartie chromatography*

You will need:

- filter paper (or blotting paper)
- some smarties in different colours
- water
- an eye dropper.

Place a smartie in the centre of a piece of filter paper. Carefully drop a few drops of water onto the smartie, until the smartie is quite wet and there is a ring of water on the filter paper. After some time you should see a coloured ring on the paper around the smartie. This is because the food colouring that is used to make the smartie colourful dissolves in the water and is carried through the paper away from the smartie.

Smartie chromatography

Photo by Neil Ravenscroft - UCT

Elements

ESAAA

An **element** is a chemical substance that can't be divided or changed into other chemical substances by any ordinary chemical means. The smallest unit of an element is the **atom**.

> ### DEFINITION: Element
> An element is a substance that cannot be broken down into other substances through chemical means.

FACT

Recently it was agreed that two more elements would be added to the list of officially named elements. These are elements number 114 and 116. The proposed name for element 114 is flerovium and for element 116 it is moscovium. This brings the total number of officially named elements to 114.

There are 112 officially named elements and about 118 known elements. Most of these are natural, but some are man-made. The elements we know are represented in the **periodic table**, where each element is abbreviated to a **chemical symbol**. Table 2.3 gives the first 20 elements and some of the common transition metals.

Element name	Element symbol	Element name	Element symbol
Hydrogen	H	Phosphorus	P
Helium	He	Sulphur	S
Lithium	Li	Chlorine	Cl
Beryllium	Be	Argon	Ar
Boron	B	Potassium	K
Carbon	C	Calcium	Ca
Nitrogen	N	Iron	Fe
Oxygen	O	Nickel	Ni
Fluorine	F	Copper	Cu
Neon	Ne	Zinc	Zn
Sodium	Na	Silver	Ag
Magnesium	Mg	Platinum	Pt
Aluminium	Al	Gold	Au
Silicon	Si	Mercury	Hg

Table 2.2: List of the first 20 elements and some common transition metals

Compounds

ESAAB

A **compound** is a chemical substance that forms when two or more different elements combine in a fixed ratio. Water (H_2O), for example, is a compound that is made up of two hydrogen atoms for every one oxygen atom. Sodium chloride (NaCl) is a compound made up of one sodium atom for every chlorine atom. An important characteristic of a compound is that it has a **chemical formula**, which describes the ratio in which the atoms of each element in the compound occur.

DEFINITION: Compound

A substance made up of two or more different elements that are joined together in a fixed ratio.

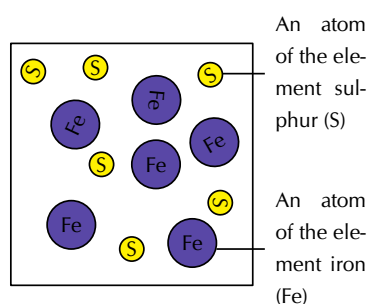
See video: VPacw at www.everythingscience.co.za

Figure 2.3 might help you to understand the difference between the terms **element**, **mixture** and **compound**. Iron (Fe) and sulphur (S) are two elements. When they are added together, they form a *mixture* of iron and sulphur. The iron and sulphur are not joined together. However, if the mixture is heated, a new **compound** is formed, which is called iron sulphide (FeS).

Note

Figure 2.3 showed a submicroscopic representation of a mixture. In a submicroscopic representation we use circles to represent different elements. To show a compound, we draw several circles joined together. Mixtures are simply shown as two or more individual elements in the same box. The circles are not joined for a mixture.

An atom of the element sulphur (S)

An atom of the element iron (Fe)

A mixture of iron and sulphur

A model of the iron sulphide crystal

We can also use symbols to represent elements, mixtures and compounds. The symbols for the elements are all found on the periodic table. Compounds are shown as two or more element names written right next to each other. Subscripts may be used to show that there is more than one atom of a particular element. (e.g. H_2O or NH_3). Mixtures are written as: a mixture of element (or compound) A and element (or compound) B. (e.g. a mixture of Fe and S).

Example 2: *Mixtures and pure substances*

QUESTION

For each of the following substances state whether it is a pure substance or a mixture. If it is a mixture, is it homogeneous or heterogeneous? If it is a pure substance is it an element or a compound?

a. *Blood (which is made up from plasma and cells)*
b. *Argon*
c. *Silicon dioxide (SiO_2)*
d. *Sand and stones*

SOLUTION

Step 1 : ***Apply the definitions***

An element is found on the periodic table, so we look at the periodic table and find that only argon appears there. Next we decide which are compounds and which are mixtures. Compounds consist of two or more elements joined in a fixed ratio. Sand and stones are not elements, neither is blood. But silicon is, as is oxygen. Finally we decide whether the mixtures are homogeneous or heterogeneous. Since we cannot see the separate components of blood it is homogeneous. Sand and stones are heterogeneous.

Step 2 : ***Write the answer***

a. Blood is a homogeneous mixture.
b. Argon is a pure substance. Argon is an element.
c. Silicon dioxide is a pure substance. It is a compound.
d. Sand and stones form a heterogeneous mixture.

Activity: *Using models to represent substances*

The following substances are given:

- Air (consists of oxygen, nitrogen, hydrogen, water vapour)
- Hydrogen gas (H_2)
- Neon gas

- Steam
- Ammonia gas (NH_3)

1. Use coloured balls to build models for each of the substances given.
2. Classify the substances according to elements, compounds, homogeneous mixtures, heterogeneous mixture, pure substance, impure substance.
3. Draw submicroscopic representations for each of the above examples.

Exercise 2 - 2

1. In the following table, tick whether each of the substances listed is a *mixture* or a *pure substance*. If it is a mixture, also say whether it is a homogeneous or heterogeneous mixture.

Substance	Mixture or pure	Homogeneous or heterogeneous mixture
fizzy colddrink		
steel		
oxygen		
iron filings		
smoke		
limestone ($CaCO_3$)		

2. In each of the following cases, say whether the substance is an element, a mixture or a compound.
   a. Cu
   b. iron and sulphur
   c. Al
   d. H_2SO_4
   e. SO_3

 More practice video solutions (?) or help at www.everythingscience.co.za

(1.) 0001 (2.) 0002

Names and formulae of substances

Think about what you call your friends. Some of your friends might have full names (long names) and a nickname (short name). These are the words we use to tell others who or what we are referring to. Their full name is like the substances name and their nickname is like the substances formulae. Without these names your friends would have no idea which of them you are referring to. Chemical substances have names, just like people have names. This helps scientists to communicate efficiently.

It is easy to describe elements and mixtures. We simply use the names that we find on the periodic table for elements and we use words to describe mixtures. But how are compounds named? In the example of iron sulphide that was used earlier, the compound name is a combination of the names of the elements but slightly changed.

See video: VPadm at www.everythingscience.co.za

The following are some guidelines for naming compounds:

1. The compound name will always include the **names of the elements** that are part of it.
   - A compound of **iron** (Fe) and *sulphur* (S) is **iron** *sulph*ide (FeS)
   - A compound of **potassium** (K) and *bromine* (Br) is **potassium** *brom*ide (KBr)
   - A compound of **sodium** (Na) and *chlorine* (Cl) is **sodium** *chlor*ide (NaCl)
2. In a compound, the element that is on the left of the Periodic Table, is used *first* when naming the compound. In the example of NaCl, sodium is a group 1 element on the left hand side of the table, while chlorine is in group 7 on the right of the table. Sodium therefore comes first in the compound name. The same is true for FeS and KBr.
3. The **symbols** of the elements can be used to represent compounds e.g. FeS, NaCl, KBr and H_2O. These are called **chemical formulae**. In the first three examples, the ratio of the elements in each compound is 1:1. So, for FeS, there is one atom of iron for every atom of sulphur in the compound. In the last example (H_2O) there are two atoms of hydrogen for every atom of oxygen in the compound.
4. A compound may contain **ions** (an ion is an atom that has lost or gained electrons). These ions can either be simple (consist of only one element) or compound (consist of several elements). Some of the more common ions and their formulae are given in Table 2.3 and in Table 2.4. You should know all these ions.

Compound ion	Formula	Compound ion	Formula	Compound ion	Formula
Hydrogen	H^+	Lithium	Li^+	Sodium	Na^+
Potassium	K^+	Silver	Ag^+	Mercury (I)	Hg^+
Copper (I)	Cu^+	Ammonium	NH_4^+	Beryllium	Be^{2+}
Magnesium	Mg^{2+}	Calcium	Ca^{2+}	Barium	Ba^{2+}
Tin (II)	Sn^{2+}	Lead (II)	Pb^{2+}	Chromium (II)	Cr^{2+}
Manganese (II)	Mn^{2+}	Iron (II)	Fe^{2+}	Cobalt (II)	Co^{2+}
Nickel	Ni^{2+}	Copper (II)	Cu^{2+}	Zinc	Zn^{2+}
Aluminium	Al^{3+}	Chromium (III)	Cr^{3+}	Iron (III)	Fe^{3+}
Cobalt (III)	Co^{3+}	Chromium (VI)	Cr^{6+}	Manganese (VII)	Mn^{7+}

Table 2.3: Table of cations

Compound ion	Formula	Compound ion	Formula
Fluoride	F^-	Oxide	O^{2-}
Chloride	Cl^-	Peroxide	O_2^{2-}
Bromide	Br^-	Carbonate	CO_3^{2-}
Iodide	I^-	Sulphide	S^{2-}
Hydroxide	OH^-	Sulphite	SO_3^{2-}
Nitrite	NO_2^-	Sulphate	SO_4^{2-}
Nitrate	NO_3^-	Thiosulphate	$S_2O_3^{2-}$
Hydrogen carbonate	HCO_3^-	Chromate	CrO_4^{2-}
Hydrogen sulphite	HSO_3^-	Dichromate	$Cr_2O_7^{2-}$
Hydrogen sulphate	HSO_4^-	Manganate	MnO_4^{2-}
Dihydrogen phosphate	$H_2PO_4^-$	Oxalate	$(COO)_2^{2-}/C_2O_4^{2-}$
Hypochlorite	ClO^-	Hydrogen phosphate	HPO_4^{2-}
Chlorate	ClO_3^-	Nitride	N^{3-}
Permanganate	MnO_4^-	Phosphate	PO_4^{3-}
Acetate (ethanoate)	CH_3COO^-	Phosphide	P^{3-}

Table 2.4: Table of anions

5. **Prefixes** can be used to describe the ratio of the elements that are in the compound.

This is used for non-metals. For metals, we add a roman number (I, II, III, IV) in brackets after the metal ion to indicate the ratio. You should know the following prefixes: "mono" (one), "di" (two) and "tri" (three).

- CO (carbon **mon**oxide) - There is one atom of oxygen for every one atom of carbon
- NO_2 (nitrogen **di**oxide) - There are two atoms of oxygen for every one atom of nitrogen
- SO_3 (sulphur **tri**oxide) - There are three atoms of oxygen for every one atom of sulphur

The above guidelines also help us to work out the formula of a compound from the name of the compound. The following worked examples will look at names and formulae in detail.

We can use these rules to help us name both ionic compounds and covalent compounds. However, covalent compounds are often given other names by scientists to simplify the name (or because the molecule was named long before its formula was discovered). For example, if we have 2 hydrogen atoms and one oxygen atom the above naming rules would tell us that the substance is dihydrogen monoxide. But this compound is better known as water!
Some common covalent compounds are given in table 2.4

Name	Formula	Name	Formula
water	H_2O	hydrochloric acid	HCl
sulphuric acid	H_2SO_4	methane	CH_4
ethane	C_2H_6	ammonia	NH_3
nitric acid	HNO_3		

Table 2.5: Names of common covalent compounds

Tip

When numbers are written as "subscripts" in compounds (i.e. they are written below and to the right of the element symbol), this tells us how many atoms of that element there are in relation to other elements in the compound. For example in nitrogen dioxide (NO_2) there are two oxygen atoms for every one atom of nitrogen. Later, when we start looking at chemical equations, you will notice that sometimes there are numbers *before* the compound name. For example, $2H_2O$ means that there are two molecules of water, and that in each molecule there are two hydrogen atoms for every one oxygen atom.

Example 3: *Writing chemical formulae 1*

QUESTION

What is formula of sodium fluoride?

SOLUTION

Step 1 : ***List the ions involved:***
We have the sodium ion (Na^+) and the fluoride ion (F^-). (You can look these up on the tables of cations and anions.)

Step 2 : ***Write down the charges on the ions***

The sodium ion has a charge of $+1$ and the fluoride ion has a charge of -1.

Step 3 : ***Find the right combination***

For every plus, we must have a minus. So the $+1$ from sodium cancels out the -1 from fluoride. They combine in a $1:1$ ratio.

Step 4 : ***Write the formula***

NaF

Example 4: *Writing chemical formulae 2*

QUESTION

What is the formula for magnesium chloride?

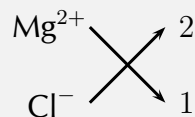
SOLUTION

Step 1 : ***List the ions involved***

Mg^{2+} and Cl^{-}

Step 2 : ***Find the right combination***

Magnesium has a charge of $+2$ and would need two chlorides to balance the charge. They will combine in a 1:2 ratio. There is an easy way to find this ratio:

Mg^{2+} ↘↗ 2
Cl^{-} ↗↘ 1

Draw a cross as above, and then you can see that Mg $\rightarrow 1$ and Cl $\rightarrow 2$.

Step 3 : ***Write down the formula***

$MgCl_2$

Example 5: *Writing chemical formulae 3*

QUESTION

Write the chemical formula for magnesium oxide.

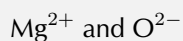
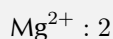
SOLUTION

Step 1 : ***List the ions involved.***

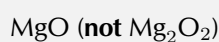
Mg^{2+} and O^{2-}

Step 2 : ***Find the right combination***

Mg^{2+} : 2

O^{2-} : 2

If you use the cross method, you will get a ratio of 2 : 2. This ratio must always be in simplest form, i.e. 1 : 1.

Step 3 : ***Write down the formula***

MgO (**not** Mg_2O_2)

Example 6: *Writing chemical formulae 4*

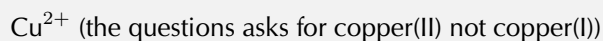
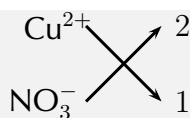
QUESTION

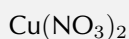
Write the formula for copper(II) nitrate.

SOLUTION

Step 1 : ***List the ions involved***

Cu^{2+} (the questions asks for copper(II) not copper(I))

NO_3^-

Step 2 : ***Find the right combination***

Step 3 : ***Write the formula***

$Cu(NO_3)_2$

Tip

Notice how in the last example we wrote NO_3^- inside brackets. We do this to indicate that NO_3^- is a compound ion and that there are two of these ions bonded to one copper ion.

Activity: *The ions dating game*

Your teacher will assign each of you a different ion (written on a piece of card). Stick this to yourself. You will also get cards with the numbers 1 - 5 on them. Now walk around the class and try to work out who you can pair up with and in what ratio. Once you have found a partner, indicate your ratio using the numbered cards. Check your results with your classmates or your teacher.

Exercise 2 - 3

1. The formula for calcium carbonate is $CaCO_3$.
   a. Is calcium carbonate an element or a compound? Give a reason for your answer.
   b. What is the ratio of Ca : C : O atoms in the formula?
2. Give the name of each of the following substances.

   a. KBr
   b. HCl
   c. $KMnO_4$
   d. NO_2
   e. NH_4OH
   f. Na_2SO_4
   g. $Fe(NO_3)_3$
   h. $PbSO_3$
   i. $Cu(HCO_3)_2$

3. Give the chemical formula for each of the following compounds.

a. potassium nitrate
b. sodium oxide
c. barium sulphate
d. aluminium chloride
e. magnesium phosphate
f. tin(II) bromide
g. manganese(II) phosphide

More practice video solutions or help at www.everythingscience.co.za

(1.) 0003 (2.) 0004 (3.) 0005

Metals, Metalloids and Non-metals

The elements in the periodic table can also be divided according to whether they are **metals**, **metalloids** or **non-metals**. The zigzag line separates all the elements that are metals from those that are non-metals. Metals are found on the left of the line, and non-metals are those on the right. Along the line you find the metalloids. You should notice that there are more metals then non-metals. Metals, metalloids and non-metals all have their own specific properties.

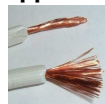
See video: VPaec at www.everythingscience.co.za

Figure 2.4: A simplified diagram showing part of the periodic table.

Metals

ESAAE

Examples of metals include copper (Cu), zinc (Zn), gold (Au), silver (Ag), tin (Sn) and lead (Pb). The following are some of the properties of metals:

Copper wire

- *Thermal conductors*
  Metals are good conductors of heat and are therefore used in cooking utensils such as pots and pans.
- *Electrical conductors*
  Metals are good conductors of electricity, and are therefore used in electrical conducting wires.
- *Shiny metallic lustre*
  Metals have a characteristic shiny appearance and are often used to make jewellery.
- *Malleable and ductile*
  This means that they can be bent into shape without breaking (malleable) and can be stretched into thin wires (ductile) such as copper.
- *Melting point*
  Metals usually have a high melting point and can therefore be used to make cooking pots and other equipment that needs to become very hot, without being damaged.
- *Density*
  Metals have a high density.
- *Magnetic properties*
  Only three main metals (iron, cobalt and nickel) are magnetic, the others are non-magnetic.

You can see how the properties of metals make them very useful in certain applications.

Activity: *Group Work : Looking at metals*

1. Collect a number of metal items from your home or school. Some examples are listed below:
   - hair clips
   - safety pins
   - cooking pots
   - jewellery
   - scissors
   - cutlery (knives, forks, spoons)
2. In groups of 3-4, combine your collection of metal objects.
3. What is the function of each of these objects?
4. Discuss why you think metal was used to make each object. You should consider the properties of metals when you answer this question.

Non-metals

ESAAF

In contrast to metals, non-metals are poor thermal conductors, good electrical insulators (meaning that they do *not* conduct electrical charge) and are neither malleable nor ductile. The non-metals include elements such as sulphur (S), phosphorus (P), nitrogen (N) and oxygen (O).

Sulphur

Picture by nickstone333 on Flickr.com

Metalloids

ESAAG

Metalloids or semi-metals have mostly non-metallic properties. One of their distinguishing characteristics is that their conductivity increases as their temperature increases.

This is the opposite of what happens in metals. This property is known as semi-conductance and the materials are called semi-conductors. Semi-conductors are important in digital electronics, such as computers. The metalloids include elements such as silicon (Si) and germanium (Ge).

Silicon chips

Picture by jurveston on Flickr.com

Electrical conductors, semi-conductors and insulators

ESAAH

> ### *DEFINITION: Electrical conductor*
>
> An electrical conductor is a substance that allows an electrical current to pass through it.

Electrical conductors are usually metals. *Copper* is one of the best electrical conductors, and this is why it is used to make conducting wire. In reality, *silver* actually has an even higher electrical conductivity than copper, but silver is too expensive to use.

See video: VPaex at www.everythingscience.co.za

In the overhead power lines that we see above us, *aluminium* is used. The aluminium usually surrounds a steel core which adds makes it stronger so that it doesn't break when it is stretched across distances. Sometimes gold is used to make wire because it is very resistant to surface corrosion. *Corrosion* is when a material starts to deteriorate because of its reactions with oxygen and water in the air.

Power lines

Picture by Tripp on Flickr.com

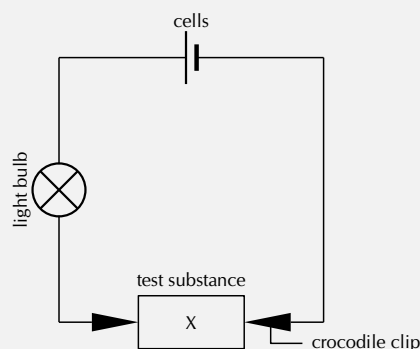
> ### *DEFINITION: Insulators*
>
> An insulator is a non-conducting material that does not carry any charge.

Examples of insulators are plastic and wood. **Semi-conductors** behave like insulators when they are cold, and like conductors when they are hot. The elements silicon and germanium are examples of semi-conductors.

General experiment: *Electrical conductivity*

Aim:
To investigate the electrical conductivity of a number of substances

Apparatus:

- two or three cells
- light bulb
- crocodile clips
- wire leads
- a selection of test substances (e.g. a piece of plastic, aluminium can, metal pencil sharpener, magnet, wood, chalk, cloth).

Method:

1. Set up the circuit as shown above, so that the test substance is held between the two crocodile clips. The wire leads should be connected to the cells and the light bulb should also be connected into the circuit.
2. Place the test substances one by one between the crocodile clips and see what happens to the light bulb. If the light bulb shines it means that current is flowing and the substance you are testing is an **electrical conductor**.

Results:
Record your results in the table below:

Test substance	Metal/non-metal	Does the light bulb glow?	Conductor or insulator

Conclusions:
In the substances that were tested, the metals were able to conduct electricity and the non-metals were not. Metals are good electrical conductors and non-metals are not.

See simulation: (Simulation: VPcyz at www.everythingscience.co.za)

Thermal Conductors and Insulators

A **thermal conductor** is a material that allows energy in the form of heat, to be transferred within the material, without any movement of the material itself. An easy way to understand this concept is through a simple demonstration.

See video: VPafb at www.everythingscience.co.za

General experiment: *Demonstration: Thermal conductivity*

Aim:
To demonstrate the ability of different substances to conduct heat.

Apparatus:

You will need:

- two cups (made from the same material e.g. plastic)
- a metal spoon
- a plastic spoon.

Method:

- Pour boiling water into the two cups so that they are about half full.
- Place a metal spoon into one cup and a plastic spoon in the other.
- Note which spoon heats up more quickly

Warning:

Be careful when working with boiling water and when you touch the spoons as you can easily burn yourself.

Results:
The metal spoon heats up faster than the plastic spoon. In other words, the metal conducts heat well, but the plastic does not.

Conclusion: Metal is a good thermal conductor, while plastic is a poor thermal conductor.

FACT

Well-insulated buildings need less energy for heating than buildings that have no insulation. Two building materials that are being used more and more worldwide, are **mineral wool** and **polystyrene**. Mineral wool is a good insulator because it holds air still in the matrix of the wool so that heat is not lost. Since air is a poor conductor and a good insulator, this helps to keep energy within the building. Polystyrene is also a good insulator and is able to keep cool things cool and hot things hot. It has the added advantage of being resistant to moisture, mould and mildew.

An **insulator** is a material that does not allow a transfer of electricity or energy. Materials that are poor thermal conductors can also be described as being good thermal insulators.

Investigation: *A closer look at thermal conductivity*

Look at the table below, which shows the thermal conductivity of a number of different materials, and then answer the questions that follow. The higher the number in the second column, the better the material is at conducting heat (i.e. it is a good thermal conductor). Remember that a material that conducts heat efficiently, will also lose heat more quickly than an insulating material.

Material	**Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)**
Silver	429
Stainless steel	16
Standard glass	1.05
Concrete	0.9 - 2
Red brick	0.69
Water	0.58
Polyethylene (plastic)	0.42 - 0.51
Wood	0.04 - 0.12
Polystyrene	0.03
Air	0.024

Use this information to answer the following questions:

1. Name two materials that are good thermal conductors.
2. Name two materials that are good insulators.
3. Explain why:
   a. Red brick is a better choice than concrete for building houses that need less internal heating.
   b. Stainless steel is good for making cooking pots

Magnetic and Non-magnetic Materials

ESAAJ

We have now looked at a number of ways in which matter can be grouped, such as into metals, semi-metals and non-metals; electrical conductors and insulators, and thermal conductors and insulators. One way in which we can further group metals, is to divide them into those that are **magnetic** and those that are **non-magnetic.**

See video: VPaga at www.everythingscience.co.za

DEFINITION: Magnetism

Magnetism is a force that certain kinds of objects, which are called 'magnetic' objects, can exert on each other without physically touching. A magnetic object is surrounded by a magnetic 'field' that gets weaker as one moves further away from the object.

A metal is said to be **ferromagnetic** if it can be magnetised (i.e. made into a magnet). If you hold a magnet very close to a metal object, it may happen that its own electrical field will be induced and the object becomes magnetic. Some metals keep their magnetism for longer than others. Look at iron and steel for example. Iron loses its magnetism quite quickly if it is taken away from the magnet. Steel on the other hand will stay magnetic for a longer time. Steel is often used to make permanent magnets that can be used for a variety of purposes.

Magnet

Photo by Aney on Wikimedia

Magnets are used to sort the metals in a scrap yard, in compasses to find direction, in the magnetic strips of video tapes and ATM cards where information must be stored, in computers and TV's, as well as in generators and electric motors.

Investigation: *Magnetism*

You can test whether an object is magnetic or not by holding another magnet close to it. If the object is attracted to the magnet, then it too is magnetic.

Find five objects in your classroom or your home and test whether they are magnetic or not. Then complete the table below:

Object	Magnetic or non-magnetic

Group Discussion: Properties of materials

In groups of 4-5, discuss how knowledge of the properties of materials has allowed::

- society to develop advanced computer technology
- homes to be provided with electricity
- society to find ways to conserve energy
- indigenous peoples to cook their food

Chapter 2 | Summary

See the summary presentation (Presentation: VPcyl at www.everythingscience.co.za)

- All the objects and substances that we see in the world are made of **matter**.
- This matter can be classified according to whether it is a **mixture** or a **pure substance**.

- A **mixture** is a combination of two or more substances, where these substances are not bonded (or joined) to each other and no chemical reaction occurs between the substances. Examples of mixtures are air (a mixture of different gases) and cereal in milk.
- The main **characteristics** of mixtures are that the substances that make them up are not in a fixed ratio, these substances keep their physical properties and these substances can be separated from each other using mechanical means.

- A **heterogeneous mixture** is one that consists of two or more substances. It is non-uniform and the different components of the mixture can be seen. An example would be a mixture of sand and water.
- A **homogeneous mixture** is one that is uniform, and where the different components of the mixture cannot be seen. An example would be salt in water.
- Pure substances can be further divided into **elements** and **compounds**.
- An **element** is a substance that cannot be broken down into other substances through chemical means.
- All the elements are found on the **periodic table**. Each element has its own chemical symbol. Examples are iron (Fe), sulphur (S), calcium (Ca), magnesium (Mg) and fluorine (F).
- A **compound** is a A substance made up of two or more different elements that are joined together in a fixed ratio. Examples of compounds are sodium chloride (NaCl), iron sulphide (FeS), calcium carbonate ($CaCO_3$) and water (H_2O).
- When **naming compounds** and writing their **chemical formula**, it is important to know the elements that are in the compound, how many atoms of each of these elements will combine in the compound and where the elements are in the periodic table. A number of rules can then be followed to name the compound.
- Another way of classifying matter is into **metals** (e.g. iron, gold, copper), **metalloids** (e.g. silicon and germanium) and **non-metals** (e.g. sulphur, phosphorus and nitrogen).

- **Metals** are good electrical and thermal conductors, they have a shiny lustre, they are malleable and ductile, and they have a high melting point. Metals also have a high density. These properties make metals very useful in electrical wires, cooking utensils, jewellery and many other applications.
- Matter can also be classified into **electrical conductors**, **semi-conductors** and **insulators**.
- An **electrical conductor** allows an electrical current to pass through it. Most metals are good electrical conductors.
- An **electrical insulator** is a non-conducting material that does not carry any charge. Examples are plastic, wood, cotton material and ceramic.
- Materials may also be classified as **thermal conductors** or **thermal insulators** depending on whether or not they are able to conduct heat.
- Materials may also be **magnetic** or **non-magnetic**. Magnetism is a force that certain kinds of objects, which are called 'magnetic' objects, can exert on each other without physically touching. A magnetic object is surrounded by a magnetic 'field' that gets weaker as one moves further away from the object.

Chapter 2 End of chapter exercises

1. Which of the following can be classified as a mixture:
   a. sugar
   b. table salt
   c. air
   d. iron
2. An element can be defined as:
   a. A substance that cannot be separated into two or more substances by ordinary chemical (or physical) means
   b. A substance with constant composition
   c. A substance that contains two or more substances, in definite proportion by weight
   d. A uniform substance
3. Classify each of the following substances as an *element*, a *compound*, a *homogeneous mixture*, or a *heterogeneous mixture*: salt, pure water, soil, salt water, pure air, carbon dioxide, gold and bronze.

4. Look at the table below. In the first column (A) is a list of substances. In the second column (B) is a description of the group that each of these substances belongs in. Match up the *substance* in Column A with the *description* in Column B.

Column A	**Column B**
1. iron	**A.** a compound containing 2 elements
2. H_2S	**B.** a heterogeneous mixture
3. sugar solution	**C.** a metal alloy
4. sand and stones	**D.** an element
5. steel	**E.** a homogeneous mixture

5. You are given a test tube that contains a mixture of iron filings and sulphur. You are asked to weigh the amount of iron in the sample.
   a. Suggest one method that you could use to separate the iron filings from the sulphur.
   b. What property of metals allows you to do this?

6. Given the following descriptions, write the chemical formula for each of the following substances:
   a. silver metal
   b. a compound that contains only potassium and bromine
   c. a gas that contains the elements carbon and oxygen in a ratio of 1:2
7. Give the names of each of the following compounds:
   a. NaBr
   b. $Ba(NO_2)_2$
   c. SO_2
   d. H_2SO_4
8. Give the formula for each of the following compounds:
   a. iron (II) sulphate
   b. boron trifluoride
   c. potassium permanganate
   d. zinc chloride
9. For each of the following materials, say what properties of the material make it important in carrying out its particular function.
   a. **tar** on roads
   b. **iron** burglar bars
   c. **plastic** furniture
   d. **metal** jewellery
   e. **clay** for building
   f. **cotton** clothing

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(1.) 0006 (2.) 0007 (3.) 0008 (4.) 0009 (5.) 000a (6.) 000b (7.) 000c (8.) 000d (9.) 000e

States of matter and the kinetic molecular theory

3

States of matter

ESAAK

In this chapter we will explore the states of matter and then look at the kinetic molecular theory. Matter exists in three states: solid, liquid and gas. We will also examine how the kinetic theory of matter helps explain boiling and melting points as well as other properties of matter.
See introductory video: (Video: VPajx at www.everythingscience.co.za)

All matter is made up of particles. We can see this when we look at diffusion.

> *DEFINITION: Diffusion*
>
> Diffusion is the movement of particles from a high concentration to a low concentration.

Diffusion can be seen as a spreading out of particles resulting in an even distribution of the particles. You can see diffusion when you place a drop of food colouring in water. The colour slowly spreads out through the water. If matter were not made of particles that are constantly moving then we would only see a clump of colour when we put the food colouring in water, as there would be nothing that could move about and mix in with the water.

Food colouring in water

Picture by LadyDayDream on Flickr.com

Diffusion is a result of the constant thermal motion of particles. In 1828 Robert Brown observed that pollen grains suspended in water moved about in a rapid, irregular motion. This motion has since become known as **Brownian motion**. Brownian motion is essentially diffusion of many particles. Brownian motion can also be seen as the random to and fro movement of particles.

Matter exists in one of three states, namely solid, liquid and gas. A solid has a fixed shape and volume. A liquid takes on the shape of the container that it is in. A gas completely fills the container that it is in. Matter can change between these states by either adding heat or removing heat. This is known as a **change of state**. As we heat an object (e.g. water) it goes from a solid to a liquid to a gas. As we cool an object it goes from a gas to a liquid to a solid. The changes of state that you should know are:

- **Melting**

> *DEFINITION: Melting point*
>
> The temperature at which a *solid* changes its phase or state to become a *liquid*. The process is called melting.

- **Freezing**

> *DEFINITION: Freezing point*
>
> The temperature at which a *liquid* changes its phase to become a *solid*. The process is called freezing.

- **Evaporation**
  Evaporation is the process of going from a liquid to a gas. Evaporation from a liquid's surface can happen at a wide range of temperatures. If more energy is added then bubbles of gas appear inside the liquid and this is known as boiling.

> *DEFINITION: Boiling point*
>
> The temperature at which a *liquid* changes its phase to become a *gas*. The process is called evaporation

- **Condensation** is the process of going from gas to liquid.
- **Sublimation** is the process of going from a solid to a gas. The reverse process is called deposition.

If we know the melting and boiling point of a substance then we can say what state (solid, liquid or gas) it will be in at any temperature.

The figure 3.1 summarises these processes:

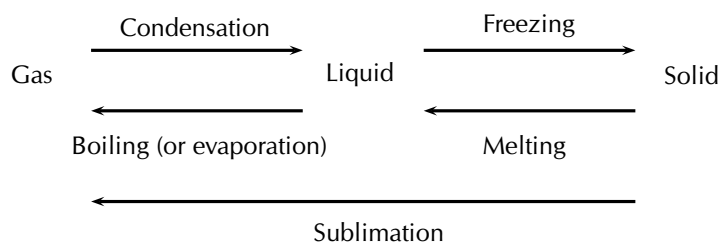
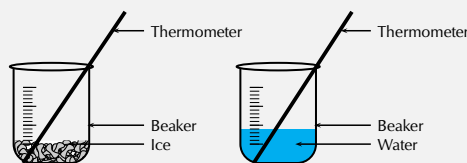



Figure 3.1: Changes in phase

Formal experiment: *Heating and cooling curve of water*

Aim: To investigate the heating and cooling curve of water.

Apparatus:

- beakers
- ice
- Bunsen burner
- thermometer
- water

Method:

1. Place some ice in a beaker.
2. Measure the temperature of the ice and record it.
3. After 1 minute measure the temperature again and record it. Repeat every minute, until at least 3 minutes after the ice has melted.
4. Plot a graph of time versus temperature for the heating of ice.
5. Heat some water in a beaker until it boils. Measure and record the temperature of the water.
6. Remove the water from the heat and measure the temperature every 1 minute, until the beaker is cool to touch.

Warning:
Be careful when handling the beaker of hot water. Do not touch the beaker with your hands, you will burn yourself.

Results:

1. Record your results in the following table:

Heating of ice		Cooling of boiling water	
Time (min)	**Temperature (in °C)**	**Time (min)**	**Temperature (in °C)**
0		0	
1		1	
2		2	
etc.		etc.	

2. Plot a graph of time (independent variable, x-axis) against temperature (dependent variable, y-axis) for the ice melting and the boiling water cooling.

Discussion and conclusion: You should find that the temperature of the ice increases until the first drops of liquid appear and then the temperature remains the same, until all the ice is melted. You should also find that when you cool water down from boiling, the temperature remains constant for a while, then starts decreasing.

In the above experiment, you investigated the heating and cooling curves of water. We can draw heating and cooling curves for any substance. A **heating curve** of a substance gives the changes in temperature as we move from a *solid* to a *liquid* to a *gas*. A **cooling curve** gives the changes in temperature as we move from *gas* to *liquid* to *solid*. An important observation is that as a substance melts or boils, the temperature remains constant until the substance has changed state. This is because all the heat energy goes into breaking or forming the bonds between the molecules.
The following diagram gives an example of what heating and cooling curves look like:

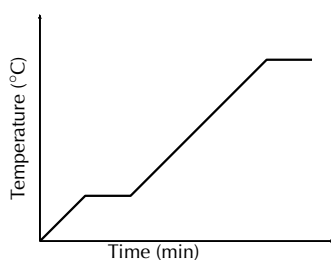



Figure 3.2: Heating curve

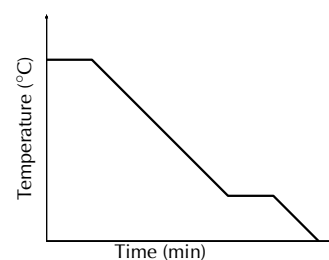



Figure 3.3: Cooling curve

The kinetic molecular theory

The **kinetic theory of matter** helps us to explain why matter exists in different *phases* (i.e. solid, liquid and gas), and how matter can change from one phase to the next. The kinetic theory of matter also helps us to understand other properties of matter. It is important to realise that what we will go on to describe is only a *theory*. It cannot be proved beyond doubt, but the fact that it helps us to explain our observations of changes in phase, and other properties of matter, suggests that it probably is more than just a theory.
Broadly, the kinetic theory of matter says that all matter is composed of **particles** which have a certain amount of **energy** which allows them to move at different speeds depending on the temperature (energy). There are **spaces** between the particles and also **attractive forces** between particles when they come close together.

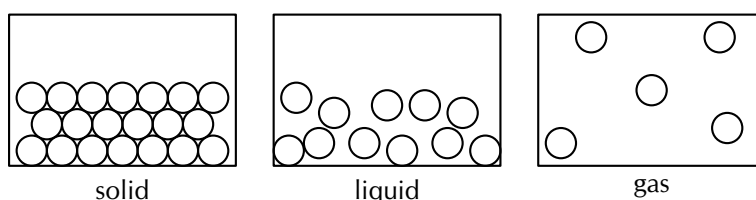



Figure 3.4: The three states of matter

Table 3.2 summarises the characteristics of the particles that are in each phase of matter.

Taking copper as an example we find that in the solid phase the copper atoms have little energy. They vibrate in fixed positions. The atoms are held closely together in a regular pattern called a *lattice*. If the copper is heated, the energy of the atoms increases. This means that some of the copper atoms are able to overcome the forces that are holding them together, and they move away from each other to form *liquid copper*. This is why liquid copper is able to flow, because the atoms are more free to move than when they were in the solid lattice. If the liquid is heated further, it will become a gas. Gas particles have lots of energy and are far away from each other. That is why it is difficult to keep a gas in a specific area! The attractive forces between the particles are very weak. Gas atoms will fill the container they are in. Figure 3.1 shows the changes in phase that may occur in matter, and the names that describe these processes.

Property of matter	Solid	Liquid	Gas
Particles	Atoms or molecules	Atoms or molecules	Atoms or molecules
Energy and movement of particles	Low energy - particles vibrate around a fixed point.	Particles have more energy than in the solid phase but less than in the gas phase.	Particles have high energy and are constantly moving.
Spaces between particles	Very little space between particles. Particles are tightly packed together.	Bigger spaces than in solids but smaller than in gases.	Large spaces because of high energy.
Attractive forces between particles.	Very strong forces. Solids have a fixed volume.	Weaker forces than in solids, but stronger forces than in gases.	Weak forces because of the large distance between particles.
Changes in phase.	Solids become liquids or gases if their temperature is increased.	A liquid becomes a gas if its temperature is increased. A liquid becomes a solid if its temperature decreases.	In general a gas becomes a liquid or solid when it is cooled. Particles have less energy and therefore move closer together so that the attractive forces become stronger, and the gas becomes a liquid or a solid.

Water can be in the form of steam, water liquid or ice. Use marbles (or playdough or clay) to represent water molecules. Arrange the marbles to show the three phases of water. Discuss the properties of each of the phases and the processes and energy in changing from the one phase to the other.

Picture by stevendepolo on Flickr.com

Picture by Alan Vernon on Flickr.com

Chapter 3 | Summary

See the summary presentation (Presentation: VPdgh at www.everythingscience.co.za)

- There are three states of matter: solid, liquid and gas.
- **Diffusion** is the movement of particles from a high concentration to a low concentration. Brownian motion is the diffusion of many particles.
- **Melting point** is the temperature at which a *solid* changes its phase to become a *liquid*. The process is called melting.
- **Freezing point** is the temperature at which a liquid changes its phase to become a solid. The process is called freezing.
- Evaporation is the process of going from a liquid to a gas. Evaporation from a liquid's surface can happen at a wide range of temperatures.
- **Boiling point** is the temperature at which a liquid changes phase to become a gas. The process is called evaporation. The reverse process (change in phase from gas to liquid) is called **condensing**.
- Sublimation is the process of going from a solid to a gas.
- The **kinetic theory of matter** attempts to explain the behaviour of matter in different phases.
- The kinetic theory of matter says that all matter is composed of **particles** which have a certain amount of **energy** which allows them to **move** at different speeds depending on the temperature (energy). There are **spaces** between the particles and also **attractive forces** between particles when they come close together.

Chapter 3 End of chapter exercises

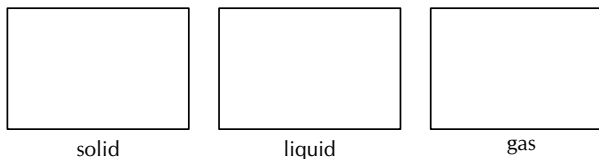
1. Give one word or term for each of the following descriptions.
   a. The change in phase from a solid to a gas.
   b. The change in phase from liquid to gas.
2. Water has a boiling point of $100°$ C
   a. Define boiling point.
   b. What change in phase takes place when a liquid reaches its boiling point?
3. Describe a solid in terms of the kinetic molecular theory.
4. Refer to the table below which gives the melting and boiling points of a number of elements and then answer the questions that follow. (*Data from http://www.chemicalelements.com*)

Element	Melting point (°C)	Boiling point (°C)
copper	1083	2567
magnesium	650	1107
oxygen	-218,4	-183
carbon	3500	4827
helium	-272	-268,6
sulphur	112,8	444,6

a. What state of matter (i.e. solid, liquid or gas) will each of these elements be in at room temperature (25°C)?

b. Which of these elements has the strongest forces between its atoms? Give a reason for your answer.

c. Which of these elements has the weakest forces between its atoms? Give a reason for your answer.

5. Complete the following submicroscopic diagrams to show what magnesium will look like in the solid, liquid and gas phase.

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(1.) 000f (2.) 000g (3.) 000h (4.) 000i (5.) 000j

The atom 4

Introduction

We have now looked at many examples of the types of matter and materials that exist around us and we have investigated some of the ways that materials are classified. But what is it that makes up these materials? And what makes one material different from another? In order to understand this, we need to take a closer look at the building blocks of matter - the **atom**. Atoms are the basis of all the structures and organisms in the universe. The planets, sun, grass, trees, air we breathe and people are all made up of different combinations of atoms.

See introductory video: (Video: VPrkk at www.everythingscience.co.za)

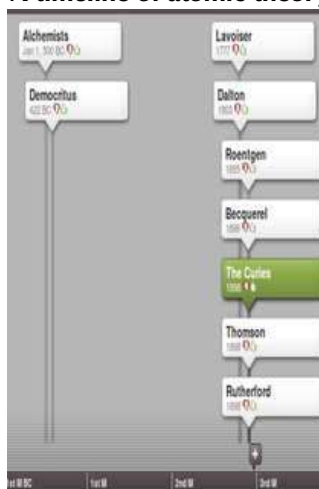
Project: **Library assignment: Models of the atom**

Our current understanding of the atom came about over a long period of time, with many different people playing a role. Conduct some research into the development of at least five different ideas of the atom and the people who contributed to it.

Some suggested people to look at are: JJ Thomson, Ernest Rutherford, Marie Curie, JC Maxwell, Max Planck, Albert Einstein, Niels Bohr, Lucretius, LV de Broglie, CJ Davisson, LH Germer, Chadwick, Werner Heisenberg, Max Born, Erwin Schrodinger, John Dalton, Empedocles, Leucippus, Democritus, Epicurus, Zosimos, Maria the Jewess, Geber, Rhazes, Robert Boyle, Henry Cavendish, A Lavoisier and H Becquerel. You do not need to find information on all these people, but try to find information about as many of them as possible. Make a list of five key contributions to a model of the atom and then make a timeline of this information. (You can use an online tool such as Dipity (http://www.dipity.com/) to make a timeline.) Try to get a feel for how it all eventually fit together into the modern understanding of the atom.

A timeline of atomic theory

Models of the atom

ESAAN

It is important to realise that a lot of what we know about the structure of atoms has been developed over a long period of time. This is often how scientific knowledge develops, with one person building on the ideas of someone else. We are going to look at how our modern understanding of the atom has evolved over time.
See video: VPakv at www.everythingscience.co.za

The idea of atoms was invented by two Greek philosophers, Democritus and Leucippus in the fifth century BC. The Greek word $\alpha\tau o\mu o\nu$ (atom) means **indivisible** because they believed that atoms could not be broken into smaller pieces.
Nowadays, we know that atoms are made up of a **positively charged nucleus** in the centre surrounded by **negatively charged electrons**. However, in the past, before the structure of the atom was properly understood, scientists came up with lots of different **models** or **pictures** to describe what atoms look like.

DEFINITION: Model

A model is a representation of a system in the real world. Models help us to understand systems and their properties.

For example, an *atomic model* represents what the structure of an atom *could* look like, based on what we know about how atoms behave. It is not necessarily a true picture of the exact structure of an atom.
Models are often simplified. The small toy cars that you may have played with as a child are models. They give you a good idea of what a real car looks like, but they are much smaller and much simpler. A model cannot always be absolutely accurate and it is important that we realise this, so that we do not build up an incorrect idea about something.

Dalton's model of the atom ESAAO

John Dalton proposed that all matter is composed of very small things which he called atoms. This was not a completely new concept as the ancient Greeks (notably Democritus) had proposed that all matter is composed of small, indivisible (cannot be divided) objects. When Dalton proposed his model electrons and the nucleus were unknown.

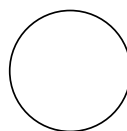



Figure 4.1: The atom according to Dalton

Thomson's model of the atom ESAAP

After the electron was discovered by J.J. Thomson in 1897, people realised that atoms were made up of even smaller particles than they had previously thought. However, the atomic nucleus had not been discovered yet and so the "plum pudding model" was put forward in 1904. In this model, the atom is made up of negative electrons that float in a "soup" of positive charge, much like plums in a pudding or raisins in a fruit cake (figure 4.2). In 1906, Thomson was awarded the Nobel Prize for his work in this field. However, even with the Plum Pudding Model, there was still no understanding of how these electrons in the atom were arranged.

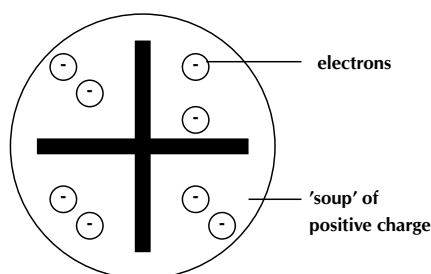



Figure 4.2: The atom according to the Plum Pudding model

FACT

Two other models proposed for the atom were the cubic model and the Saturnian model. In the cubic model, the electrons were imagined to lie at the corners of a cube. In the Saturnian model, the electrons were imagined to orbit a very big, heavy nucleus.

The discovery of **radiation** was the next step along the path to building an accurate picture of atomic structure. In the early twentieth century, Marie and Pierre Curie, discovered that some elements (the *radioactive* elements) emit particles, which are able to pass through matter in a similar way to X-rays (read more about this in Grade 11). It was Ernest Rutherford who, in 1911, used this discovery to revise the model of the atom.

Rutherford's model of the atom ESAAQ

Rutherford carried out some experiments which led to a change in ideas around the atom. His new model described the atom as a tiny, dense, positively charged core called a nucleus surrounded by lighter, negatively charged electrons. Another way of thinking about this model was that the atom was seen to be like a mini solar system where the electrons orbit the nucleus like planets orbiting around the sun. A simplified picture of this is shown alongside. This model is sometimes known as the planetary model of the atom.

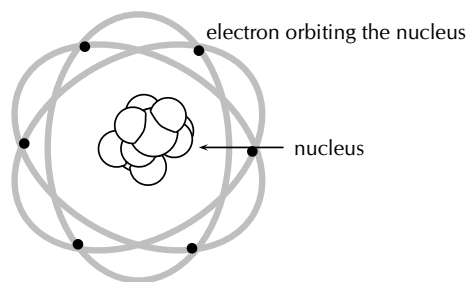



Figure 4.3: Rutherford's model of the atom

Bohr's model of the atom

There were, however, some problems with Rutherford's model: for example it could not explain the very interesting observation that atoms only emit light at certain wavelengths or frequencies. Niels Bohr solved this problem by proposing that the electrons could only orbit the nucleus in certain special orbits at different energy levels around the nucleus.

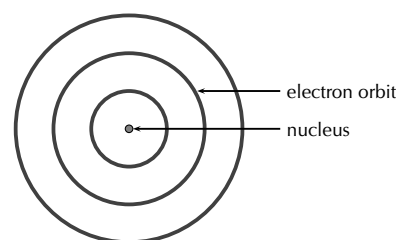



Figure 4.4: Bohr's model of the atom

James Chadwick

Rutherford predicted (in 1920) that another kind of particle must be present in the nucleus along with the proton. He predicted this because if there were only positively charged protons in the nucleus, then it should break into bits because of the repulsive forces between the like-charged protons! To make sure that the atom stays electrically neutral, this particle would have to be neutral itself. In 1932 James Chadwick discovered the neutron

and measured its mass.

Other models of the atom

ESAAT

Although the most commonly used model of the atom is the Bohr model, scientists are still developing new and improved theories on what the atom looks like. One of the most important contributions to atomic theory (the field of science that looks at atoms) was the development of quantum theory. Schrodinger, Heisenberg, Born and many others have had a role in developing quantum theory.

Exercise 4 - 1

Match the information in column A, with the key discoverer in column B.

Column A	Column B
1. Discovery of electrons and the plum pudding model	**A.** Niels Bohr
2. Arrangement of electrons	**B.** Marie and Pierre Curie
3. Atoms as the smallest building block of matter	**C.** Ancient Greeks and Dalton
4. Discovery of the nucleus	**D.** JJ Thomson
5. Discovery of radiation	**E.** Rutherford

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(1.) 000k

Atomic mass and diameter

ESAAU

It is difficult sometimes to imagine the size of an atom, or its mass, because we cannot see an atom and also because we are not used to working with such small measurements.

How heavy is an atom? ESAAV

It is possible to determine the mass of a single atom in kilograms. But to do this, you would need special instruments and the values you would get would be very clumsy and difficult to work with. The mass of a carbon atom, for example, is about $1,99 \times 10^{-26}$ kg, while the mass of an atom of hydrogen is about $1,67 \times 10^{-27}$ kg. Looking at these very small numbers makes it difficult to compare how much bigger the mass of one atom is when compared to another.
To make the situation simpler, scientists use a different unit of mass when they are describing the mass of an atom. This unit is called the **atomic mass unit** (amu). We can abbreviate (shorten) this unit to just u. Scientists use the **carbon standard** to determine amu. The carbon standard gives carbon an atomic mass of $12,0$ u. Compared to carbon the mass of a hydrogen atom will be 1 u. Atomic mass units are therefore not giving us the *actual* mass of an atom, but rather its mass *relative* to the mass of one (carefully chosen) atom in the periodic table. In other words it is only a number in comparison to another number. The atomic masses of some elements are shown in table 4.1.

Element	Atomic mass (u)
Carbon (C)	$12,0$
Nitrogen (N)	$14,0$
Bromine (Br)	$79,9$
Magnesium (Mg)	$24,3$
Potassium (K)	$39,1$
Calcium (Ca)	$40,1$
Oxygen (O)	$16,0$

Table 4.1: The atomic mass number of some of the elements.

The actual value of 1 atomic mass unit is $1,67 \times 10^{-24}$ g or $1,67 \times 10^{-27}$ kg. This is a very tiny mass! If we write it out it looks like this: $0,000\ 000\ 000\ 000\ 000\ 000\ 000\ 000\ 167$ kg. An atom is therefore very very small.

Rutherford's alpha-particle scattering experiment ESAAW

Radioactive elements emit different types of particles. Some of these are positively charged alpha (α) particles. Rutherford wanted to find out where the positive charge in an atom is. He carried out a series of experiments where he bombarded sheets of gold foil with alpha particles (since these would be repelled by the positive nucleus). A simplified diagram of his experiment is shown in figure 4.5.

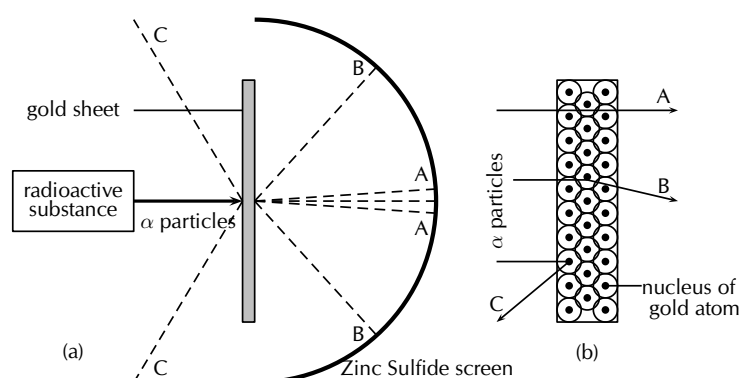



Figure 4.5: Rutherford's gold foil experiment. Figure (a) shows the path of the α particles after they hit the gold sheet. Figure (b) shows the arrangement of atoms in the gold sheets and the path of the α particles in relation to this.

See video: VPald at www.everythingscience.co.za

Rutherford set up his experiment so that a beam of alpha particles was directed at the gold sheets. Behind the gold sheets was a screen made of zinc sulphide. This screen allowed Rutherford to see where the alpha particles were landing. Rutherford knew that the *electrons* in the gold atoms would not really affect the path of the alpha particles, because the mass of an electron is so much smaller than that of a proton. He reasoned that the positively charged *protons* would be the ones to *repel* the positively charged alpha particles and alter their path.

If Thomson's model of the atom was correct then Rutherford would have observed mostly path C in figure 4.5. (C represents alpha particles that are reflected by the positive nucleus). What he found instead was that most of the alpha particles passed through the foil undisturbed and could be detected on the screen directly behind the foil (path A). Some of the particles ended up being slightly deflected onto other parts of the screen (path B). The fact that most particles passed straight through suggested that the positive charge was concentrated in one part of the atom only.

Through this experiment he concluded that the nucleus of the atom is positively charged

and situated in the middle of the atom.

How small is the nucleus? ESAAX

The nucleus of an atom is very small. We can compare an atom with a soccer stadium. If the whole atom is as big as a soccer stadium, the nucleus is only the size of a pea in the middle of the stadium! This should help you see that the atom is mainly made up of empty space. If you removed all the empty space from the atoms in your body, you would become the size of a grain of salt!

A stadium

Picture by Shine 2010 on Flickr.com

Relative atomic mass ESAAY

DEFINITION: Relative atomic mass

The relative atomic mass of an element is the average mass of all the naturally occurring isotopes of that element. The units for relative atomic mass are atomic mass units.

The relative atomic mass of an element is the number you will find on the periodic table.

Structure of the atom ESAAZ

As a result of the work done by previous scientists on atomic models, scientists now have a good idea of what an atom looks like. This knowledge is important because it helps us to understand why materials have different properties and why some materials bond with others. Let us now take a closer look at the microscopic structure of the atom (what the atom looks like inside).

See video: VPaln at www.everythingscience.co.za

So far, we have discussed that atoms are made up of a positively charged **nucleus** surrounded by one or more negatively charged **electrons**. These electrons orbit the nucleus. Before we look at some useful concepts we first need to understand what electrons, protons and neutrons are.

The Electron

The electron is a very tiny particle. It has a mass of $9,11 \times 10^{-31}$ kg. The electron carries one unit of negative electric charge (i.e. $-1,6 \times 10^{-19}$ C).

The Nucleus

Unlike the electron, the nucleus **can** be broken up into smaller building blocks called **protons** and **neutrons**. Together, the protons and neutrons are called **nucleons**.

FACT

Scientists believe that the electron can be treated as a **point particle** or **elementary particle** meaning that it cannot be broken down into anything smaller.

The Proton

The electron carries one unit of **negative** electric charge (i.e. $-1,6\times10^{-19}$ C, C is Coulombs). Each proton carries one unit of **positive** electric charge (i.e. $+1,6 \times 10^{-19}$ C). Since we know that atoms are **electrically neutral**, i.e. do not carry any extra charge, then the number of protons in an atom has to be the same as the number of electrons to balance out the positive and negative charge to zero. The total positive charge of a nucleus is equal to the number of protons in the nucleus. The proton is much heavier than the electron ($10\ 000$ times heavier!) and has a mass of $1,6726 \times 10^{-27}$ kg. When we talk about the atomic mass of an atom, we are mostly referring to the combined mass of the protons and neutrons, i.e. the nucleons.

The Neutron

The neutron is electrically neutral i.e. it carries no charge at all. Like the proton, it is much heavier than the electron and its mass is $1,6749 \times 10^{-27}$ kg (slightly heavier than the proton).

	proton	neutron	electron
Mass (kg)	$1,6726 \times 10^{-27}$	$1,6749 \times 10^{-27}$	$9,11 \times 10^{-31}$
Units of charge	$+1$	0	-1
Charge (C)	$1,6 \times 10^{-19}$	0	$-1,6 \times 10^{-19}$

Table 4.2: Summary of the particles inside the atom

Atomic number and atomic mass number ESABC

The chemical properties of an element are determined by the charge of its nucleus, i.e. by the **number of protons**. This number is called the **atomic number** and is denoted by the letter **Z**.

FACT

Currently element 118 is the highest atomic number for an element. Elements of high atomic numbers (from about 93 to 118) do not exist for long as they break apart within seconds of being formed. Scientists believe that after element 118 there may be an "island of stability" in which elements of higher atomic number occur that do not break apart within seconds.

DEFINITION: Atomic number (Z)

The number of protons in an atom

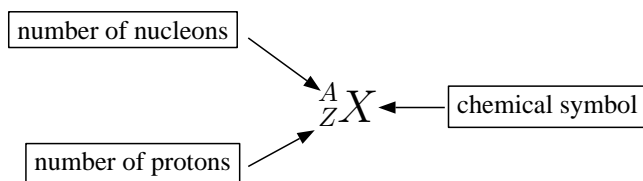
You can find the atomic number on the periodic table (see periodic table at front of book). The atomic number is an integer and ranges from 1 to about 118.

The mass of an atom depends on how many nucleons its nucleus contains. The number of nucleons, i.e. the total number of protons **plus** neutrons, is called the **atomic mass number** and is denoted by the letter **A**.

DEFINITION: Atomic mass number (A)

The number of protons and neutrons in the nucleus of an atom

The atomic number (Z) and the mass number (A) are indicated using a standard notation, for example carbon will look like this: $^{12}_{6}$C

Standard notation shows the chemical symbol, the atomic mass number and the atomic number of an element as follows:

For example, the iron nucleus which has 26 protons and 30 neutrons, is denoted as:

$$^{56}_{26}\text{Fe}$$

where the atomic number is $Z = 26$ and the mass number $A = 56$. The number of neutrons is simply the difference $N = A - Z = 30$.

For a neutral atom the number of electrons is the same as the number of protons, since the charge on the atom must balance. But what happens if an atom gains or loses electrons? Does it mean that the atom will still be part of the same element? A change in the number of electrons of an atom does not change the type of atom that it is. However, the charge of the atom will change. The *neutrality* of the atom has changed. If electrons are *added*, then the atom will become more *negative*. If electrons are *taken away* then the atom will become more *positive*. The atom that is formed in either of these two cases is called an **ion**. An ion is a charged atom. For example: a neutral sodium atom can lose one electron to become a positively charged sodium atom (Na^+). A neutral chlorine atom can gain one electron to become a negatively charged chlorine ion (Cl^-). Another example is Li^+ which has lost one electron and now has only 2 electrons, instead of 3. Or consider F^- which has gained one electron and now has 10 electrons instead of 9.

FACT

A nuclide is a distinct kind of atom or nucleus characterised by the number of protons and neutrons in the atom. To be absolutely correct, when we represent atoms like we do here, then we should call them nuclides.

Tip

Do not confuse the notation we have used here with the way this information appears on the periodic table. On the periodic table, the atomic number usually appears in the top left-hand corner of the block or immediately above the element's symbol. The number below the element's symbol is its **relative atomic mass**. This is not exactly the same as the atomic mass number. This will be explained in "Isotopes". The example of iron is shown below.

Example 1: *Standard notation*

QUESTION

Use standard notation to represent sodium and give the number of protons, neutrons and electrons in the element.

SOLUTION

Step 1 : ***Give the element symbol***
Na

Step 2 : ***Find the number of protons***
Sodium has 11 protons, so we have: $_{11}\text{Na}$

Step 3 : ***Find the number of electrons***

Sodium is neutral, so it has the same number of electrons as protons. The number of electrons is 11.

Step 4 : ***Find A***

From the periodic table we see that $A = 23$.

Step 5 : ***Work out the number of neutrons***

We know A and Z so we can find N: $N = A - Z = 23 - 11 = 12$.

Step 6 : ***Write the answer***

In standard notation sodium is given by: $^{23}_{11}$Na. The number of protons is 11, the number of neutrons is 12 and the number of electrons is 11.

Exercise 4 - 2

1. Explain the meaning of each of the following terms:
   a. nucleus
   b. electron
   c. atomic mass
2. Complete the following table:

Element	Atomic mass units	Atomic number	Number of protons	Number of electrons	Number of neutrons
Mg	24	12			
O			8		
		17			
Ni				28	
	40				20
Zn					
					0
C	12			6	
Al^{3+}		13			
O^{2-}				18	

3. Use standard notation to represent the following elements:
   a. potassium
   b. copper
   c. chlorine
4. For the element $^{35}_{17}$Cl, give the number of...
   a. protons
   b. neutrons
   c. electrons

   ... in the atom.

5. Which of the following atoms has 7 electrons?
   a. $^{5}_{2}$He
   b. $^{13}_{6}$C
   c. $^{7}_{3}$Li
   d. $^{15}_{7}$N
6. In each of the following cases, give the number or the element symbol represented by X.
   a. $^{40}_{18}$X
   b. $^{x}_{20}$Ca
   c. $^{31}_{x}$P
7. Complete the following table:

	A	Z	N
$^{235}_{92}$U			
$^{238}_{92}$U			

   In these two different forms of uranium...
   a. What is the *same*?
   b. What is *different*?

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(1.) 000m (2.) 000n (3.) 000p (4.) 000q (5.) 000r (6.) 000s (7.) 000t

Isotopes

ESABD

FACT

In Greek, "same place" reads as ἰσος τόπος (isos topos). This is why atoms which have the same number of protons, but different numbers of neutrons, are called *isotopes*. They are in the same place on the periodic table!

The chemical properties of an element depend on the number of protons and electrons inside the atom. So if a neutron or two is added or removed from the nucleus, then the chemical properties will not change. This means that such an atom would remain in the same place in the periodic table. For example, no matter how many neutrons we add or subtract from a nucleus with 6 protons, that element will **always** be called carbon and have the element symbol C (see the periodic table). Atoms which have the same number of protons (i.e. same atomic number Z), but a different number of neutrons (i.e. different N and therefore different mass number A), are called **isotopes**.

DEFINITION: Isotope

Isotopes of an element have the same number of protons (same Z), but a different number of neutrons (different N).

The chemical properties of the different isotopes of an element are the same, but they might vary in how stable their nucleus is. We can also write elements as E - A where the E is the element symbol and the A is the atomic mass of that element. For example Cl-35 has an atomic mass of 35 u (17 protons and 18 **neutrons**), while Cl-37 has an atomic mass of 37 u (17 protons and 20 **neutrons**).
In nature the different isotopes occur in different percentages. For example Cl-35 might make up 75% of all chlorine atoms on Earth, and Cl-37 makes up the remaining 25%. The following worked example will show you how to calculate the average atomic mass for these two isotopes:

Example 2: *The relative atomic mass of an isotopic element*

QUESTION

The element chlorine has two isotopes, chlorine-35 and chlorine-37. The abundance of these isotopes when they occur naturally is 75% chlorine-35 and 25% chlorine-37.

Calculate the average relative atomic mass for chlorine.

SOLUTION

Step 1 : ***Calculate the mass contribution of chlorine-35 to the average relative atomic mass***

75% of the chlorine atoms has a mass of of 35 u

Contribution of Cl-$35 = (\frac{75}{100} \times 35) = 26,25$ u

Step 2 : ***Calculate the contribution of chlorine-37 to the average relative atomic mass***

25% of the chlorine atoms has a mass of of 37 u

Contribution of Cl-$37 = (\frac{25}{100} \times 37) = 9,25$ u

Step 3 : ***Add the two values to arrive at the average relative atomic mass of chlorine***

$$\text{Relative atomic mass of chlorine} = 26,25 \text{ u} + 9,25 \text{ u} = 35,5 \text{ u}$$

If you look on the periodic table (see front of book), the average relative atomic mass for chlorine is $35,5$ u. See simulation: (Simulation: VPcyv at www.everythingscience.co.za)

Exercise 4 - 3

1. Atom A has 5 protons and 5 neutrons, and atom B has 6 protons and 5 neutrons. These atoms are:
   a. allotropes
   b. isotopes
   c. isomers
   d. atoms of different elements
2. For the sulphur isotopes, $^{32}_{16}$S and $^{34}_{16}$S, give the number of:
   a. protons
   b. nucleons
   c. electrons
   d. neutrons
3. Which of the following are isotopes of $^{35}_{17}$Cl?
   a. $^{17}_{35}$Cl
   b. $^{35}_{17}$Cl
   c. $^{37}_{17}$Cl

4. Which of the following are isotopes of U-235? (E represents an element symbol)

- **a**. $^{238}_{92}$E
- **b**. $^{238}_{90}$E
- **c**. $^{235}_{92}$E

5. Complete the table below:

Isotope	Z	A	Protons	Neutrons	Electrons
Carbon-12					
Carbon-14					
Iron-54					
Iron-56					
Iron-57					

6. If a sample contains $19,9\%$ boron-10 and $80,1\%$ boron-11, calculate the relative atomic mass of an atom of boron in that sample.

7. If a sample contains 79% Mg-24, 10% Mg-25 and 11% Mg-26, calculate the relative atomic mass of an atom of magnesium in that sample.

8. For the element $^{234}_{92}$U (uranium), use standard notation to describe:

- **a**. the isotope with 2 fewer neutrons
- **b**. the isotope with 4 more neutrons

9. Which of the following are isotopes of $^{40}_{20}$Ca?

- **a**. $^{40}_{19}$K
- **b**. $^{42}_{20}$Ca
- **c**. $^{40}_{18}$Ar

10. For the sulphur isotope $^{33}_{16}$S, give the number of:

- **a**. protons
- **b**. nucleons
- **c**. electrons
- **d**. neutrons

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(1.) 000x (2.) 000y (3.) 000z (4.) 0010 (5.) 0011 (6.) 0012

(7.) 0013 (8.) 0014 (9.) 0015 (10.) 0016

Electronic configuration ESABE

The energy of electrons ESABF

The electrons of an atom all have the same charge and the same mass, but each electron has a different amount of *energy*. Electrons that have the *lowest* energy are found closest to the nucleus (where the attractive force of the positively charged nucleus is the greatest) and the electrons that have *higher* energy (and are able to overcome the attractive force of the nucleus) are found further away.

See video: VPama at www.everythingscience.co.za

Electron arrangement ESABG

We will start with a very simple view of the arrangement or configuration of electrons around an atom. This view simply states that electrons are arranged in energy levels (or shells) around the nucleus of an atom. These energy levels are numbered 1, 2, 3, etc. Electrons that are in the first energy level (energy level 1) are closest to the nucleus and will have the lowest energy. Electrons further away from the nucleus will have a higher energy.

In the following examples, the energy levels are shown as concentric circles around the central nucleus. The important thing to know for these diagrams is that the first energy level can hold 2 electrons, the second energy level can hold 8 electrons and the third energy level can hold 8 electrons.

1. **Lithium**
   Lithium (Li) has an atomic number of 3, meaning that in a neutral atom, the number of electrons will also be 3. The first two electrons are found in the first energy level, while the third electron is found in the second energy level (Figure 4.6).

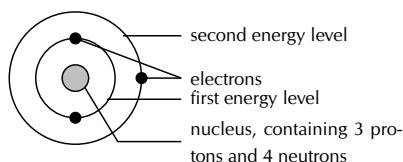



Figure 4.6: Electron arrangement of a lithium atom.

2. **Fluorine**

Fluorine (F) has an atomic number of 9, meaning that a neutral atom also has 9 electrons. The first 2 electrons are found in the first energy level, while the other 7 are found in the second energy level (Figure 4.7).

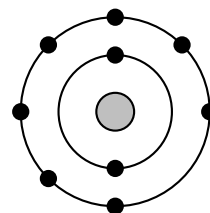



Figure 4.7: Electron arrangement of a fluorine atom.

3. **Neon**

Neon (Ne) has an atomic number of 10, meaning that a neutral atom also has 10 electrons. The first 2 electrons are found in the first energy level and the last 8 are found in the second energy level. (Figure 4.8).

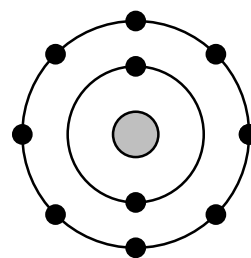



Figure 4.8: Electron arrangement of a neon atom.

But the situation is slightly more complicated than this. Within each energy level, the electrons move in **orbitals**. An orbital defines the spaces or regions where electrons move.

DEFINITION: Atomic orbital

An atomic orbital is the region in which an electron may be found around a single atom.

Note

Each block in figure 4.9 is able to hold two electrons. This means that the s orbital can hold two electrons, while the p orbital can hold a total of six electrons, two in each of the three blocks.

The first energy level contains only one s orbital, the second energy level contains one s orbital and three p orbitals and the third energy level contains one s orbital and three p orbitals (as well as five d orbitals). Within each energy level, the s orbital is at a lower energy than the p orbitals. This arrangement is shown in Figure 4.9.

This diagram also helps us when we are working out the electron configuration of an element. The electron configuration of an element is the arrangement of the electrons in the shells and subshells. There are a few guidelines for working out the electron configuration. These are:

- Each orbital can only hold **two electrons**. Electrons that occur together in an orbital are called an **electron pair**.
- An electron will always try to enter an orbital with the lowest possible energy.

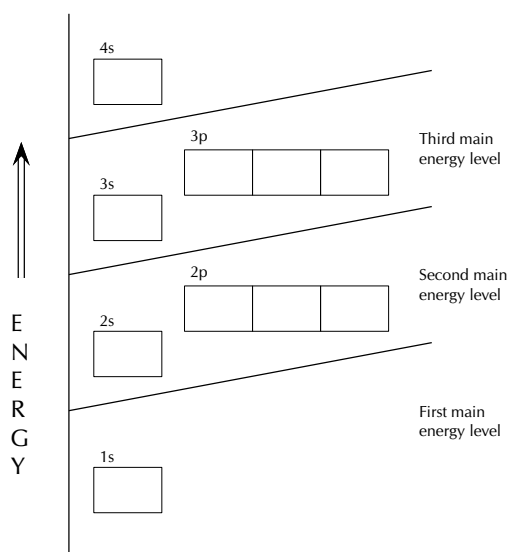



Figure 4.9: The positions of the first ten orbitals of an atom on an energy diagram.

- An electron will occupy an orbital on its own, rather than share an orbital with another electron. An electron would also rather occupy a lower energy orbital *with* another electron, before occupying a higher energy orbital. In other words, within one energy level, electrons will fill an s orbital before starting to fill p orbitals.
- The s subshell can hold 2 electrons
- The p subshell can hold 6 electrons

Tip

When there are two electrons in an orbital, the electrons are called an **electron pair**. If the orbital only has one electron, this electron is said to be an **unpaired electron**. Electron pairs are shown with arrows pointing in opposite directions.

The way that the electrons are arranged in an atom is called its **electron configuration**.

DEFINITION: Electron configuration

Electron configuration is the arrangement of electrons in an atom, molecule or other physical structure.

Aufbau diagrams

 ESABH

An element's electron configuration can be represented using **Aufbau diagrams** or energy level diagrams. An Aufbau diagram uses arrows to represent electrons. You can use the following steps to help you to draw an Aufbau diagram:

1. Determine the number of electrons that the atom has.
2. Fill the s orbital in the first energy level (the 1s orbital) with the first two electrons.
3. Fill the s orbital in the second energy level (the 2s orbital) with the second two electrons.
4. Put one electron in each of the three p orbitals in the second energy level (the 2p orbitals) and then if there are still electrons remaining, go back and place a second electron in each of the 2p orbitals to complete the electron pairs.
5. Carry on in this way through each of the successive energy levels until all the electrons have been drawn.

FACT

Aufbau is the German word for "building up". Scientists used this term since this is exactly what we are doing when we work out electron configuration, we are building up the atoms structure.

You can think of Aufbau diagrams as being similar to people getting on a bus or a train. People will first sit in empty seats with empty seats between them and the other people (unless they know the people and then they will sit next to them). This is the lowest energy. When all the seats are filled like this, any more people that get on will be forced to sit next to someone. This is higher in energy. As the bus or train fills even more the people have to stand to fit on. This is the highest energy.

Hund's rule and Pauli's principle

Sometimes people refer to Hund's rule for electron configuration. This rule simply says that electrons would rather be in a subshell on their own than share a subshell. This is why when you are filling the subshells you put one electron in each subshell and then go back and fill the subshell, before moving onto the next energy level.

Pauli's exclusion principle simply states that electrons have a property known as spin and that two electrons in a subshell will not spin the same way. This is why we draw electrons as one arrow pointing up and one arrow pointing down.

Spectroscopic electron configuration notation

A special type of notation is used to show an atom's electron configuration. The notation describes the energy levels, orbitals and the number of electrons in each. For example, the electron configuration of lithium is $1s^2 2s^1$. The number and letter describe the energy level and orbital and the number above the orbital shows how many electrons are in that orbital.

Aufbau diagrams for the elements fluorine and argon are shown in Figures 4.10 and 4.11 respectively. Using spectroscopic notation, the electron configuration of fluorine is $1s^2 2s^2 2p^5$ and the electron configuration of argon is $1s^2 2s^2 2p^5 3s^2 3p^6$.

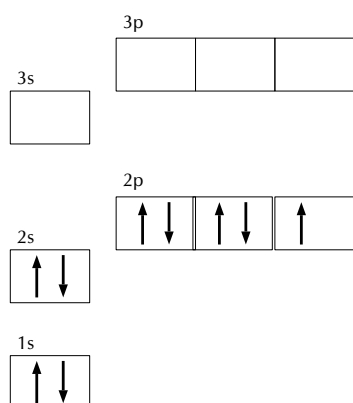



Figure 4.10: An Aufbau diagram showing the electron configuration of fluorine

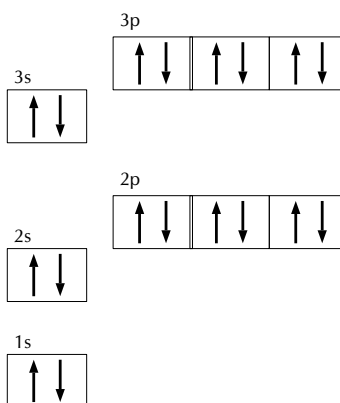



Figure 4.11: An Aufbau diagram showing the electron configuration of argon

Tip

The spectroscopic electron configuration can be written in shorter form. This form is written as [noble gas]electrons, where the noble gas is the nearest one that occurs before the element. For example, magnesium can be represented as [Ne]$3s^2$ and carbon as [H]$2s^2 2p^2$. This is known as the condensed electron configuration.

Example 3: *Aufbau diagrams and spectroscopic electron configuration*

QUESTION

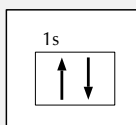
Give the electron configuration for nitrogen (N) and draw an Aufbau diagram.

SOLUTION

Step 1 : ***Give the number of electrons***

Nitrogen has seven electrons.

Step 2 : ***Place two electrons in the 1s orbital***

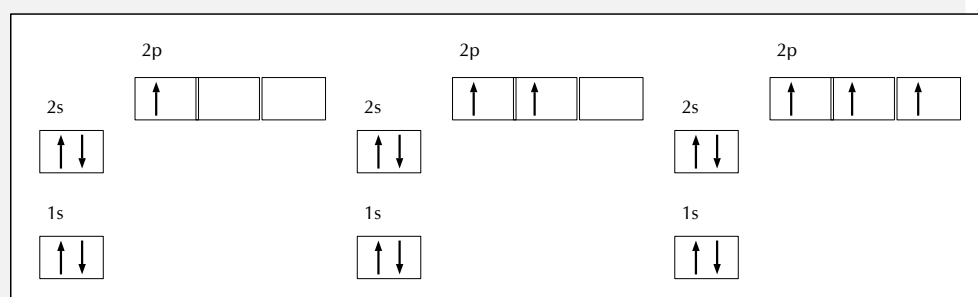
We start by placing two electrons in the 1s orbital: $1s^2$.

Now we have five electrons left to place in orbitals.

Step 3 : ***Place two electrons in the 2s orbital***

We put two electrons in the 2s orbital: $2s^2$.

There are now three electrons to place in orbitals.

Step 4 : ***Place three electrons in the 2p orbital***

We place three electrons in the 2p orbital: $2p^3$.

Step 5 : ***Write the final answer***

The electron configuration is: $1s^2 2s^2 2p^3$. The Aufbau diagram is given in the step above.

Aufbau diagrams for ions

When a neutral atom loses an electron it becomes positively charged and we call it a cation. For example, sodium will lose one electron and become Na^+ or calcium will lose two electrons and become Ca^{2+}. In each of these cases, the outermost electron(s) will be lost.

When a neutral atom gains an electron it becomes negatively charged and we call it an anion. For example chlorine will gain one electron and become Cl^- or oxygen will gain two electrons and become O^{2-}.

Aufbau diagrams and electron configurations can be done for cations and anions as well. The following worked example will show you how.

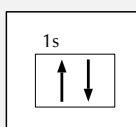
Example 4: *Aufbau diagram for an ion*

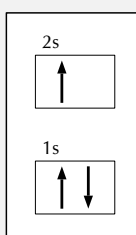
QUESTION

Give the electron configuration for (O^{2-}) and draw an Aufbau diagram.

SOLUTION

Step 1 : ***Give the number of electrons***
Oxygen has eight electrons. The oxygen anion has gained two electrons and so the total number of electrons is ten.

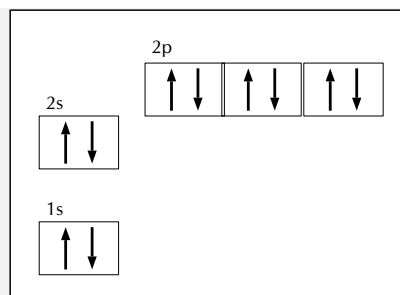
Step 2 : ***Place two electrons in the 1s orbital***
We start by placing two electrons in the 1s orbital: $1s^2$.

Now we have eight electrons left to place in orbitals.

Step 3 : ***Place two electrons in the 2s orbital***
We put two electrons in the 2s orbital: $2s^2$.

There are now six electrons to place in orbitals.

Step 4 : ***Place six electrons in the 2p orbital***
We place six electrons in the 2p orbital: $2p^6$.

Step 5 : ***Write the final answer***
The electron configuration is: $1s^2 2s^2 2p^6$. The Aufbau diagram is:

FACT

When we draw the orbitals we draw a shape that has a boundary (i.e. a closed shape). This represents the distance from the nucleus in which we are 95% sure that we will find the electrons. In reality the electrons of an atom could be found any distance away from the nucleus.

Orbital shapes ESABJ

Each of the orbitals has a different shape. The s orbitals are spherical and the p orbitals are dumbbell shaped.

Figure 4.12: The orbital shapes. From left to right: an s orbital, a p orbital, the three p orbitals

Core and valence electrons

Electrons in the outermost energy level of an atom are called **valence electrons**. The electrons that are in the energy shells closer to the nucleus are called **core electrons**. Core electrons are all the electrons in an atom, excluding the valence electrons. An element that has its valence energy level full is *more stable* and *less likely to react* than other elements with a valence energy level that is not full.

DEFINITION: Valence electrons

The electrons in the outermost energy level of an atom

DEFINITION: Core electrons

All the electrons in an atom, excluding the valence electrons

Exercise 4 - 4

Complete the following table:

Element or Ion	**Electron configuration**	**Core electrons**	**Valence electrons**
Potassium (K)			
Helium (He)			
Oxygen ion (O^{2-})			
Magnesium ion (Mg^{2+})			

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(1.) 0017

The importance of understanding electron configuration ESABL

By this stage, you may well be wondering why it is important for you to understand how electrons are arranged around the nucleus of an atom. Remember that during chemical

reactions, when atoms come into contact with one another, it is the *electrons* of these atoms that will interact first. More specifically, it is the **valence electrons** of the atoms that will determine how they react with one another.

To take this a step further, an atom is at its most stable (and therefore *unreactive*) when all its orbitals are full. On the other hand, an atom is least stable (and therefore most *reactive*) when its valence electron orbitals are not full. This will make more sense when we go on to look at chemical bonding in a later chapter. To put it simply, the valence electrons are largely responsible for an element's chemical behaviour and elements that have the same number of valence electrons often have similar chemical properties.

The most stable configurations are the ones that have full energy levels. These configurations occur in the noble gases. The noble gases are very stable elements that do not react easily (if at all) with any other elements. This is due to the full energy levels. All elements would like to reach the most stable electron configurations, i.e. all elements want to be noble gases. This principle of stability is sometimes referred to as the octet rule. An octet is a set of 8, and the number of electrons in a full energy level is 8.

See video: VPamk at www.everythingscience.co.za

Informal experiment: *Flame tests*

Aim: To determine what colour a metal cation will cause a flame to be.

Apparatus:

- Watch glass
- Bunsen burner
- methanol
- tooth picks (or skewer sticks)
- metal salts (e.g. NaCl, $CuCl_2$, $CaCl_2$, KCl, etc.)
- metal powders (e.g. copper, magnesium, zinc, iron, etc.)

Picture by offbeatcin on Flickr.com

Warning:

Be careful when working with Bunsen burners as you can easily burn yourself. Make sure all scarves/loose clothing are securely tucked in and long hair is tied back. Ensure that you work in a well-ventilated space and that there is nothing flammable near the open flame.

Method: For each salt or powder do the following:

1. Dip a clean tooth pick into the methanol
2. Dip the tooth pick into the salt or powder
3. Wave the tooth pick through the flame from the Bunsen burner. DO NOT hold the tooth pick in the flame, but rather wave it back and forth through the flame.
4. Observe what happens

Results: Record your results in a table, listing the metal salt and the colour of the flame.
Conclusion: You should have observed different colours for each of the metal salts and powders that you tested.

The above experiment on flame tests relates to the line emission spectra of the metals. These line emission spectra are a direct result of the arrangement of the electrons in metals. Each metal salt has a uniquely coloured flame.

Exercise 4 - 5

1. Draw Aufbau diagrams to show the electron configuration of each of the following elements:

   a. magnesium
   b. potassium
   c. sulphur
   d. neon
   e. nitrogen

2. Use the Aufbau diagrams you drew to help you complete the following table:

Element	No. of energy levels	No. of electrons	Electron configuration (standard notation)
Mg			
K			
S			
Ne			
N			
Ca^{2+}			
Cl^{-}			

3. Rank the elements used above in order of *increasing reactivity*. Give reasons for the order you give.

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(1.-3.) 0018

Earlier in this chapter, we talked about different "models" of the atom. In science, one of the uses of models is that they can help us to understand the structure of something that we can't see. In the case of the atom, models help us to build a picture in our heads of what the atom looks like.

Group Discussion: Building a model of an atom

In groups of 3-4, you are going to build a model of an atom. Each group will get a different element to represent. Before you start, think about these questions:

- What information do I have about the structure of the atom? (e.g. what parts make it up? how big is it?)
- What materials can I use to represent these parts of the atom as accurately as I can?
- How will I put all these different parts together in my model?

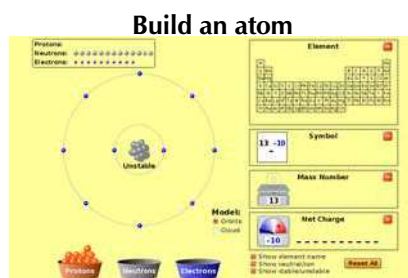
As a group, share your ideas and then plan how you will build your model. Once you have built your model, discuss the following questions:

- Does our model give a good idea of what the atom actually looks like?
- In what ways is our model *inaccurate*? For example, we know that electrons *move* around the atom's nucleus, but in your model, it might not have been

possible for you to show this.

- Are there any ways in which our model could be improved?

Now look at what other groups have done. Discuss the same questions for each of the models you see and record your answers.

Build an atom

See simulation: (Simulation: VPcmk at www.everythingscience.co.za)

See simulation: (Simulation: VPcph at www.everythingscience.co.za)

Chapter 4 | Summary

See the summary presentation (Presentation: VPcre at www.everythingscience.co.za)

- Some of the scientists who have contributed to the theory of the atom include **J.J.Thomson** (discovery of the electron, which led to the Plum Pudding Model of the atom), **Marie and Pierre Curie** (work on radiation), **Ernest Rutherford** (discovery that positive charge is concentrated in the centre of the atom) and **Niels Bohr** (the arrangement of electrons around the nucleus in energy levels).
- Because of the very small mass of atoms, their mass is measured in **atomic mass units** (u). $1 \text{ u} = 1,67 \times 10^{-24} \text{ g}$.
- The **relative atomic mass** of an element is the average mass of all the naturally occurring isotopes of that element. The units for relative atomic mass are atomic mass units. The relative atomic mass is written under the elements' symbol on the periodic table.
- An atom is made up of a central **nucleus** (containing **protons** and **neutrons**), surrounded by **electrons**. Most of the atom is empty space.
- The **atomic number** (Z) is the number of protons in an atom.
- The **atomic mass number** (A) is the number of protons and neutrons in the nucleus of an atom.

- The **standard notation** that is used to write an element, is $^A_Z X$, where X is the element symbol, A is the atomic mass number and Z is the atomic number.
- The **isotope** of a particular element is made up of atoms which have the same number of protons as the atoms in the original element, but a different number of neutrons. This means that not all atoms of an element will have the same atomic mass.
- Within each energy level, an electron may move within a particular shape of **orbital**. An orbital defines the space in which an electron is most likely to be found.
- The **electron configuration** is the arrangement of electrons in an atom, molecule or other physical structure.
- Energy diagrams such as **Aufbau diagrams** are used to show the electron configuration of atoms.
- The electron configuration of an atom can be given using spectroscopic notation.
- Different orbitals have different shapes: s orbitals are spherically shaped and p orbitals are dumbbell shaped.
- The electrons in the outermost energy level are called **valence electrons**.
- The electrons in an atom that are not valence electrons are called **core electrons**.
- Atoms whose outermost energy level is full, are less chemically reactive and therefore more stable, than those atoms whose outermost energy level is not full.

Chapter 4 End of chapter exercises

1. Write down only the word/term for each of the following descriptions.
   a. The sum of the number of protons and neutrons in an atom
   b. The defined space around an atom's nucleus, where an electron is most likely to be found
2. For each of the following, say whether the statement is true or false. If it is false, re-write the statement correctly.
   a. $^{20}_{10}Ne$ and $^{22}_{10}Ne$ each have 10 protons, 12 electrons and 12 neutrons.
   b. The atomic mass of any atom of a particular element is always the same.
   c. It is safer to use helium gas rather than hydrogen gas in balloons.
   d. Group 1 elements readily form negative ions.
3. The three basic components of an atom are:
   a. protons, neutrons, and ions
   b. protons, neutrons, and electrons
   c. protons, neutrinos, and ions
   d. protium, deuterium, and tritium
4. The charge of an atom is:
   a. positive

- **b**. neutral
   - **c**. negative
   - **d**. none of the above
5. If Rutherford had used neutrons instead of alpha particles in his scattering experiment, the neutrons would:
   - **a**. not deflect because they have no charge
   - **b**. have deflected more often
   - **c**. have been attracted to the nucleus easily
   - **d**. have given the same results
6. Consider the isotope $^{234}_{92}$U. Which of the following statements is *true*?
   - **a**. The element is an isotope of $^{234}_{94}$Pu
   - **b**. The element contains 234 neutrons
   - **c**. The element has the same electron configuration as $^{238}_{92}$U
   - **d**. The element has an atomic mass number of 92
7. The electron configuration of an atom of chlorine can be represented using the following notation:
   - **a**. $1s^2 2s^8 3s^7$
   - **b**. $1s^2 2s^2 2p^6 3s^2 3p^5$
   - **c**. $1s^2 2s^2 2p^6 3s^2 3p^6$
   - **d**. $1s^2 2s^2 2p^5$
8. Give the standard notation for the following elements:
   - **a**. beryllium
   - **b**. carbon-12
   - **c**. titanium-48
   - **d**. fluorine
9. Give the electron configurations and Aufbau diagrams for the following elements:
   - **a**. aluminium
   - **b**. phosphorus
   - **c**. carbon
   - **d**. oxygen ion
   - **e**. calcium ion
10. For each of the following elements give the number of protons, neutrons and electrons in the element:
   - **a**. $^{195}_{78}$Pt
   - **b**. $^{40}_{18}$Ar
   - **c**. $^{59}_{27}$Co
   - **d**. $^{7}_{3}$Li
   - **e**. $^{11}_{5}$B
11. For each of the following elements give the element or number represented by x:
   - **a**. $^{103}_{45}$X
   - **b**. $^{35}_{x}$Cl

c. ${}^{x}_{4}Be$

12. Which of the following are isotopes of ${}^{24}_{12}Mg$:

a. ${}^{12}_{25}Mg$

b. ${}^{26}_{12}Mg$

c. ${}^{24}_{13}Al$

13. If a sample contains 69% of copper-63 and 31% of copper-65, calculate the relative atomic mass of an atom in that sample.

14. Complete the following table:

Element or ion	Electron configuration	Core electrons	Valence electrons
Boron (B)			
Calcium (Ca)			
Silicon (Si)			
Lithium ion (Li^{+})			
Neon (Ne)			

More practice video solutions or help at www.everythingscience.co.za

(1.) 0019 (2.) 001a (3.) 001b (4.) 001c (5.) 001d (6.) 001e

(7.) 001f (8.) 001g (9.) 001h (10.) 001i (11.) 001j (12.) 001k

(13.) 001m (14.) 001n

The periodic table 5

The arrangement of the elements

ESABM

The **periodic table of the elements** is a method of showing the chemical elements in a table with the elements arranged in order of increasing atomic number. Most of the work that was done to arrive at the periodic table that we know can be attributed to a Russian chemist named **Dmitri Mendeleev**. Mendeleev designed the table in 1869 in such a way that recurring ("periodic") trends or patterns in the properties of the elements could be shown. Using the trends he observed, he left gaps for those elements that he thought were "missing". He also predicted the properties that he thought the missing elements would have when they were discovered. Many of these elements were indeed discovered and Mendeleev's predictions were proved to be correct.
See introductory video: (Video: VParg at www.everythingscience.co.za)

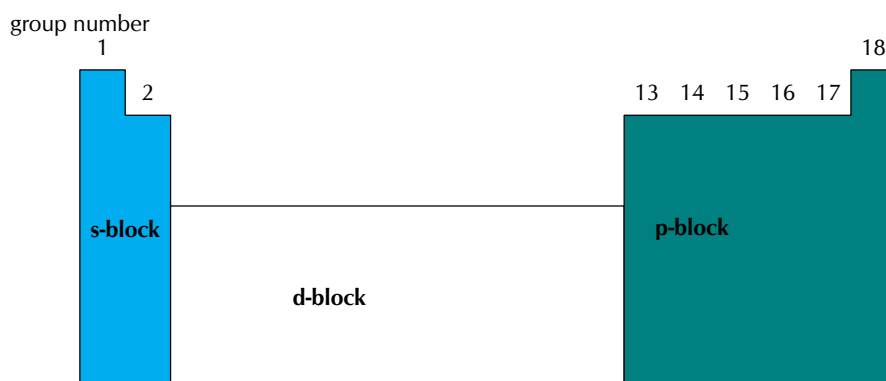
To show the recurring properties that he had observed, Mendeleev began new rows in his table so that elements with similar properties were in the same vertical columns, called **groups**. Each row was referred to as a **period**. Figure 5.3 shows a simplified version of the periodic table. The full periodic table is reproduced at the front of this book. You can view an online periodic table at *http://periodictable.com/*.

Figure 5.1: A simplified diagram showing part of the periodic table. Metals are given in gray, metalloids in light blue and non-metals in turquoise.

Definitions and important concepts

Before we can talk about the trends in the periodic table, we first need to define some terms that are used:

- **Atomic radius**
  The atomic radius is a measure of the size of an atom.
- **Ionisation energy**
  The first ionisation energy is the energy needed to remove one electron from an atom in the gas phase. The ionisation energy is different for each element. We can also define second, third, fourth, etc. ionisation energies. These are the energies needed to remove the second, third, or fourth electron respectively.
- **Electron affinity**
  Electron affinity can be thought of as how much an element wants electrons.
- **Electronegativity**
  Electronegativity is the tendency of atoms to attract electrons. The electronegativity of the elements starts from about 0.7 (Francium (Fr)) and goes up to 4 (Fluorine (F))
- A **group** is a vertical column in the periodic table and is considered to be the most important way of classifying the elements. If you look at a periodic table, you will see the groups numbered at the top of each column. The groups are numbered from left to right starting with 1 and ending with 18. This is the convention that we will use in this book. On some periodic tables you may see that the groups are numbered from left to right as follows: 1, 2, then an open space which contains the **transition elements**, followed by groups 3 to 8. Another way to label the groups is using Roman numerals.
- A **period** is a horizontal row in the periodic table of the elements. The periods are labelled from top to bottom, starting with 1 and ending with 7.

For each element on the periodic table we can give its period number and its group number. For example, B is in period 2 and group 13. We can also determine the electronic structure of an element from its position on the periodic table. In chapter 4 you worked out the electronic configuration of various elements. Using the periodic table we can easily give the electronic configurations of any element. To see how this works look at the following:

We also note that the period number gives the energy level that is being filled. For example, phosphorus (P) is in the third period and group 15. Looking at the figure above, we see that the p-orbital is being filled. Also the third energy level is being filled. So its electron configuration is: [Ne]$3s^2 3p^3$. (Phosphorus is in the third group in the p-block, so it must have 3 electrons in the p shell.)

Periods in the periodic table ESABO

The following diagram illustrates some of the key trends in the periods:

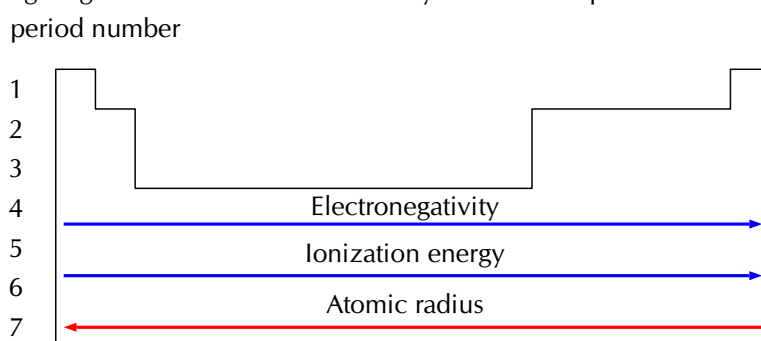



Figure 5.2: Trends on the periodic table.

See video: VParr at www.everythingscience.co.za

Table 5.1 summarises the patterns or trends in the properties of the elements in period 3. Similar trends are observed in the other periods of the periodic table. The chlorides are compounds with chlorine and the oxides are compounds with oxygen.

Element	$^{23}_{11}$Na	$^{24}_{12}$Mg	$^{27}_{13}$Al	$^{28}_{14}$Si	$^{31}_{15}$P	$^{32}_{16}$S	$^{35}_{17}$Cl
Chlorides	NaCl	$MgCl_2$	$AlCl_3$	$SiCl_4$	PCl_5 or PCl_3	S_2Cl_2	no chlorides
Oxides	Na_2O	MgO	Al_2O_3	SiO_2	P_4O_6 or P_4O_{10}	SO_3 or SO_4	Cl_2O_7 or Cl_2O
Valence electrons	$3s^1$	$3s^2$	$3s^23p^1$	$3s^23p^2$	$3s^23p^3$	$3s^23p^4$	$3s^23p^5$
Atomic radius	Decreases across a period.						
First Ionization energy	The general trend is an increase across the period.						
Electronegativity	Increases across the period.						
Melting and boiling point	Increases to silicon and then decreases to argon.						
Electrical conductivity	Increases from sodium to aluminium. Silicon is a semi-conductor. The rest are insulators.						

Table 5.1: Summary of the trends in period 3

Note that we have left argon ($^{40}_{18}$Ar) out. Argon is a noble gas with electron configuration: [Ne]$3s^23p^6$. Argon does not form any compounds with oxygen or chlorine.

Exercise 5 - 1

1. Use Table 5.1 and Figure 5.2 to help you produce a similar table for the elements in period 2.
2. Refer to the data table below which gives the ionisation energy (in $kJ \cdot mol^{-1}$) and atomic number (Z) for a number of elements in the periodic table:

Z	Name of element	Ionization energy	Z	Name of element	Ionization energy
1		1310	10		2072
2		2360	11		494
3		517	12		734
4		895	13		575
5		797	14		783
6		1087	15		1051
7		1397	16		994
8		1307	17		1250
9		1673	18		1540

a. Fill in the names of the elements.
b. Draw a line graph to show the relationship between atomic number (on the x-axis) and ionisation energy (y-axis).
c. Describe any trends that you observe.
d. Explain why:

  i. the ionisation energy for $Z = 2$ is higher than for $Z = 1$
  ii. the ionisation energy for $Z = 3$ is lower than for $Z = 2$
  iii. the ionisation energy increases between $Z = 5$ and $Z = 7$

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(1.) 001p (2.) 001q

Chemical properties of the groups

ESABP

In some groups, the elements display very similar chemical properties and some of the groups are even given special names to identify them. The characteristics of each group are mostly determined by the electron configuration of the atoms of the elements in the group. The names of the groups are summarised in Figure 5.3

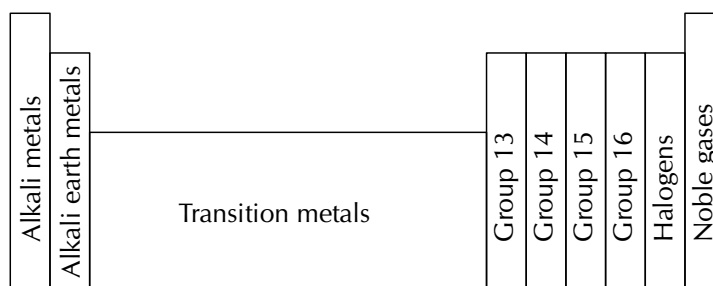



Figure 5.3: Groups on the periodic table

A few points to note about the groups are:

- Although hydrogen appears in group 1, it is not an alkali metal.
- Group 15 elements are sometimes called the pnictogens.
- Group 16 elements are sometimes known as the chalcogens.
- The **halogens** and the **alkali earth metals** are very reactive groups.
- The **noble gases** are *inert* (unreactive).

See video: VPasj at www.everythingscience.co.za

The following diagram illustrates some of the key trends in the groups of the periodic table:

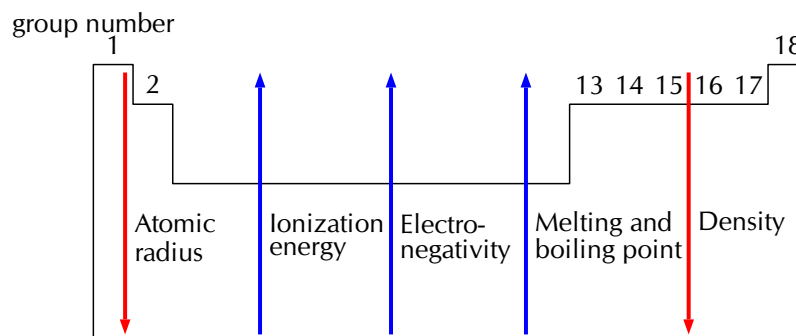



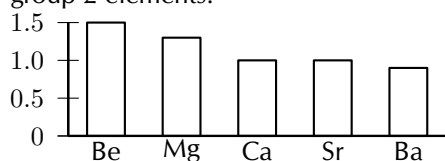
Figure 5.4: Trends in the groups on the periodic table.

Table 5.2 summarises the patterns or trends in the properties of the elements in group 1. Similar trends are observed for the elements in the other groups of the periodic table. We can use the information in 5.2 to predict the chemical properties of unfamiliar elements. For example, given the element Francium (Fr) we can say that its electronic structure will be [Rn]$7s^1$, it will have a lower first ionisation energy than caesium (Cs) and its melting and boiling point will also be lower than caesium.
You should also recall from chapter 2 that the metals are found on the left of the periodic table, non-metals are on the right and metalloids are found on the zig-zag line that starts at boron.

Element	${}^{7}_{3}$Li	${}^{7}_{3}$Na	${}^{7}_{3}$K	${}^{7}_{3}$Rb	${}^{7}_{3}$Cs
Electron structure	[He]$2s^1$	[Ne]$3s^1$	[Ar]$4s^1$	[Kr]$4s^1$	[Xe]$5s^1$
Group 1 chlorides	LiCl	NaCl	KCl	RbCl	CsCl
	Group 1 elements all form halogen compounds in a 1:1 ratio				
Group 1 oxides	Li_2O	Na_2O	K_2O	Rb_2O	Cs_2O
	Group 1 elements all form oxides in a 2:1 ratio				
Atomic radius	Increases as you move down the group.				
First ionisation energy	Decreases as you move down the group.				
Electronegativity	Decreases as you move down the group.				
Melting and boiling point	Decreases as you move down the group.				
Density	Increases as you move down the group.				

Table 5.2: Summary of the trends in group 1

Exercise 5 - 2

1. Use Table 5.2 and Figure 5.4 to help you produce similar tables for group 2 and group 17.
2. The following two elements are given. Compare these elements in terms of the following properties. Explain the differences in each case. ${}^{24}_{12}$Mg and ${}^{40}_{20}$Ca.
   a. Size of the atom (atomic radius)
   b. Electronegativity
   c. First ionisation energy
   d. Boiling point
3. Study the following graph and explain the trend in electronegativity of the group 2 elements.

4. Refer to the elements listed below:

- Lithium (Li)
- Chlorine (Cl)
- Magnesium (Mg)
- Neon (Ne)
- Oxygen (O)
- Calcium (Ca)
- Carbon (C)

Which of the elements listed above:

a. belongs to Group 1
b. is a halogen
c. is a noble gas
d. is an alkali metal
e. has an atomic number of 12
f. has four neutrons in the nucleus of its atoms
g. contains electrons in the 4th energy level
h. has all its energy orbitals full
i. will have chemical properties that are most similar

   or help at www.everythingscience.co.za

(1.) 001r (2.) 001s (3.) 001t (4.) 001u

Activity:	*Inventing your own periodic table*

You are the official chemist for the planet Zog. You have discovered all the same elements that we have here on Earth, but you don't have a periodic table. The citizens of Zog want to know how all these elements relate to each other. How would you invent the periodic table? Think about how you would organise the data that you have and what properties you would include. Do not simply copy Mendeleev's ideas, be creative and come up with some of your own. Research other forms of the periodic table and make one that makes sense to you. Present your ideas to your class.

Circular periodic table

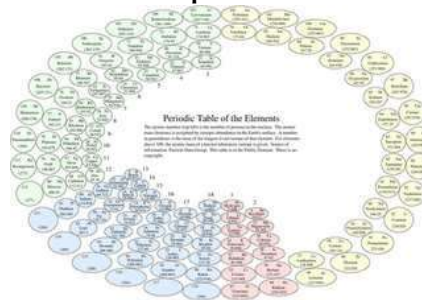



Image from Wikimedia commons

Chapter 5 | Summary

See the summary presentation (▶ Presentation: VPddg at www.everythingscience.co.za)

- Elements are arranged in periods and groups on the periodic table. The elements are arranged according to increasing atomic number.
- A **group** is a column on the periodic table containing elements with similar properties. A **period** is a row on the periodic table.
- The atomic radius is a measure of the size of the atom.
- The first ionisation energy is the energy needed to remove one electron from an atom in the gas phase.
- Electronegativity is the tendency of atoms to attract electrons.
- Across a period the ionisation energy and electronegativity increase. The atomic radius decreases across a period.
- The groups on the periodic table are labelled from 1 to 18. Group 1 is known as the alkali metals, group 2 is known as the alkali earth metals, group 17 is known as the halogens and the group 18 is known as the noble gases. The elements in a group have similar properties.
- The atomic radius and the density both increase down a group. The ionisation energy, electronegativity, and melting and boiling points all decrease down a group.

Chapter 5 End of chapter exercises

1. For the following questions state whether they are true or false. If they are false, correct the statement
   a. The group 1 elements are sometimes known as the alkali earth metals.
   b. The group 8 elements are known as the noble gases.
   c. Group 7 elements are very unreactive.
   d. The transition elements are found between groups 3 and 4.
2. Give one word or term for each of the following:
   a. The energy that is needed to remove one electron from an atom
   b. A horizontal row on the periodic table
   c. A very reactive group of elements that is missing just one electron from their outer shells.
3. Given $^{80}_{35}Br$ and $^{35}_{17}Cl$. Compare these elements in terms of the following properties. Explain the differences in each case.
   a. Atomic radius
   b. Electronegativity

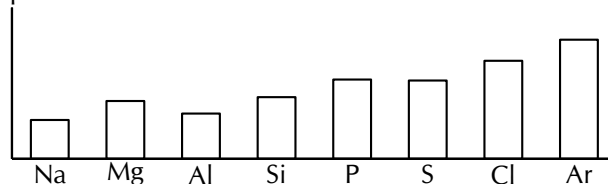
c. First ionisation energy
d. Boiling point

4. Given the following table:

Element	Na	Mg	Al	Si	P	S	Cl	Ar
Atomic number	11	12	13	14	15	16	17	18
Density ($g \cdot cm^{-3}$)	0,97	1,74	2,70	2,33	1,82	2,08	3,17	1,78
Melting point ($^{\circ}C$)	370,9	923,0	933,5	1687	317,3	388,4	171,6	83,8
Boiling point ($^{\circ}C$)	1156	1363	2792	3538	550	717,8	239,1	87,3
Electronegativity	0.93	1.31	1.61	1.90	2.19	2.58	3.16	-

Draw graphs to show the patterns in the following physical properties:

a. Density
b. Boiling point
c. Melting point
d. Electronegativity

5. A graph showing the pattern in first ionisation energy for the elements in period 3 is shown below:

a. Explain the pattern by referring to the electron configuration
b. Predict the pattern in the first ionisation energy for the elements in period 2.
c. Draw a rough graph to show the pattern predicted in the previous question.

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(1.) 001v (2.) 001w (3.) 001x (4.) 001y (5.) 001z

Chemical bonding 6

Introduction ESABQ

When you look at everything around you and what it is made of, you will realise that atoms seldom exist on their own. More often, the things around us are made up of different atoms that have been joined together. This is called **chemical bonding**. Chemical bonding is one of the most important processes in chemistry because it allows all sorts of different molecules and combinations of atoms to form, which then make up the objects in the complex world around us.

See introductory video: (Video: VPawb at www.everythingscience.co.za)

What happens when atoms bond? ESABR

A **chemical bond** is formed when atoms are held together by attractive forces. This attraction occurs when electrons are *shared* between atoms, or when electrons are *exchanged* between the atoms that are involved in the bond. The sharing or exchange of electrons takes place so that the outer energy levels of the atoms involved are filled, making the atoms are more stable. If an electron is **shared**, it means that it will spend its time moving in the electron orbitals around *both* atoms. If an electron is **exchanged** it means that it is transferred from one atom to another. In other words one atom *gains* an electron while the other *loses* an electron.

DEFINITION: Chemical bond

A chemical bond is the physical process that causes atoms and molecules to be attracted to each other and held together in more stable chemical compounds.

The type of bond that is formed depends on the elements that are involved. In this chapter, we will be looking at three types of chemical bonding: **covalent**, **ionic** and **metallic**

bonding.

You need to remember that it is the *valence electrons* (those in the outermost level) that are involved in bonding and that atoms will try to fill their outer energy levels so that they are more stable. The noble gases have completely full outer energy levels, so are very stable and do not react easily with other atoms.

Lewis structures *ESABS*

> **Tip**
>
> If we write the condensed electron configuration, then we can easily see the valence electrons.

Lewis notation uses dots and crosses to represent the **valence electrons** on different atoms. The chemical symbol of the element is used to represent the nucleus and the inner electrons of the atom. To determine which are the valence electrons we look at the last *energy level* in the atom's electronic structure (chapter 4). For example, chlorine's electronic structure can be written as:$1s^2 2s^2 2p^6 3s^2 3p^5$ or [Ne]$3s^2 3p^5$. The last energy level is the third one and it contains 7 electrons. These are the valence electrons.

For example:

A hydrogen atom (one valence electron) would be represented like this: **H •**

A chlorine atom (seven valence electrons) would look like this:

A molecule of hydrogen chloride would be shown like this:

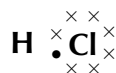
H •× Cl

The dot and cross in between the two atoms, represent the pair of electrons that are shared in the covalent bond.

Table 6.1 gives some further examples of Lewis diagrams.

Iodine	I_2	I × • I
Water	H_2O	H •× O ו H
Carbon dioxide	CO_2	O ••×× C ××•• O
Hydrogen cyanide	HCN	H •× C ×ו•× N

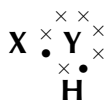
Table 6.1: Lewis diagrams for some simple molecules

For carbon dioxide, you can see how we represent a double bond in Lewis notation. As there are two bonds between each oxygen atom and the carbon atom, two pairs of valence electrons link them. Similarly, hydrogen cyanide shows how to represent a triple bond.

Exercise 6 - 1

1. Represent each of the following *atoms* using Lewis notation:
   a. beryllium
   b. calcium
   c. lithium
2. Represent each of the following *molecules* using Lewis notation:
   a. bromine gas (Br_2)
   b. carbon dioxide (CO_2)

   Which of these two molecules contains a double bond?
3. Two chemical reactions are described below.
   - nitrogen and hydrogen react to form NH_3
   - carbon and hydrogen bond to form a molecule of CH_4

   For each reaction, give:
   a. the number of electrons in the outermost energy level
   b. the Lewis structure of the product that is formed
   c. the name of the product
4. A chemical compound has the following Lewis notation:

   a. How many valence electrons does element Y have?
   b. What is the valency of element Y? (remember that the valency of an atom is the number of chemical bonds it can form.)
   c. What is the valency of element X?
   d. How many covalent bonds are in the molecule?
   e. Suggest a name for the elements X and Y.

(1.) 0020 (2.) 0021 (3.) 0022 (4.) 0023

Covalent Bonding ESABT

The nature of the covalent bond ESABU

Covalent bonding occurs between the atoms of **non-metals**. The outermost orbitals of the atoms overlap so that unpaired electrons in each of the bonding atoms can be shared. By overlapping orbitals, the outer energy shells of all the bonding atoms are filled. The shared electrons move in the orbitals around *both* atoms. As they move, there is an attraction between these negatively charged electrons and the positively charged nuclei. This attractive force holds the atoms together in a covalent bond.

See video: VPaxf at www.everythingscience.co.za

Tip

There is a relationship between the valency of an element and its position on the periodic table. For the elements in groups 1 and 2, the valency is the group number. For the elements in groups 13 - 18, the valency is the group number minus 10. For the transition metals, the valency can vary. In these cases we indicate the valency by a roman numeral after the element name, e.g. iron (III) chloride.

DEFINITION: Covalent bond

Covalent bonding is a form of chemical bonding where pairs of electrons are shared between atoms.

You will have noticed in table 6.1 that the number of electrons that are involved in bonding varies between atoms. We can say the following:

- A **single covalent** bond is formed when two electrons are shared between the same two atoms, one electron from each atom.
- A **double covalent** bond is formed when four electrons are shared between the same two atoms, two electrons from each atom.
- A **triple covalent** bond is formed when six electrons are shared between the same two atoms, three electrons from each atom.

You should also have noticed that compounds can have a mixture of single, double and triple bonds and that an atom can have several bonds. In other words, an atom does not need to share all its valence electrons with one other atom, but can share its valence electrons with several different atoms.
We say that the **valency** of the atoms is different.

DEFINITION: Valency

The number of electrons in the outer shell of an atom which are able to be used to form bonds with other atoms.

Below are a few examples. Remember that it is only the *valence electrons* that are involved in bonding and so when diagrams are drawn to show what is happening during bonding, it is only these electrons that are shown.

Example 1: *Covalent bonding*

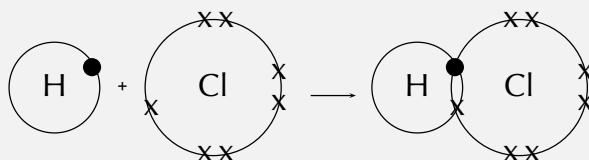
QUESTION

How do hydrogen and chlorine atoms bond covalently in a molecule of hydrogen chloride?

SOLUTION

Step 1 : ***Determine the electron configuration of each of the bonding atoms.***
A chlorine atom has 17 electrons and an electron configuration of $[Ne]3s^{2}3p^{5}$. A hydrogen atom has only one electron and an electron configuration of $1s^{1}$.

Step 2 : ***Determine how many of the electrons are paired or unpaired.***
Chlorine has seven valence electrons. One of these electrons is unpaired. Hydrogen has one valence electron and it is unpaired.

Step 3 : ***Work out how the electrons are shared***
The hydrogen atom needs one more electron to complete its outermost energy level. The chlorine atom also needs one more electron to complete its outermost energy level. Therefore *one pair of electrons* must be shared between the two atoms. A single covalent bond will be formed.

Example 2: *Covalent bonding involving multiple bonds*

QUESTION

How do nitrogen and hydrogen atoms bond to form a molecule of ammonia (NH_3)?

SOLUTION

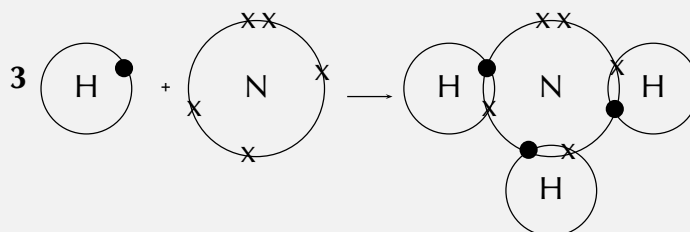
Step 1 : ***Give the electron configuration***

A nitrogen atom has seven electrons, and an electron configuration of [He]$2s^2 2p^3$. A hydrogen atom has only one electron, and an electron configuration of $1s^1$.

Step 2 : ***Give the number of valence electrons***

Nitrogen has five valence electrons. Three of these electrons are unpaired. Hydrogen has one valence electron and it is unpaired.

Step 3 : ***Work out how the electrons are shared***

Each hydrogen atom needs one more electron to complete its valence energy shell. The nitrogen atom needs three more electrons to complete its valence energy shell. Therefore *three pairs of electrons* must be shared between the four atoms involved. Three single covalent bonds will be formed.

Example 3: *Covalent bonding involving a double bond*

QUESTION

How do oxygen atoms bond covalently to form an oxygen molecule?

SOLUTION

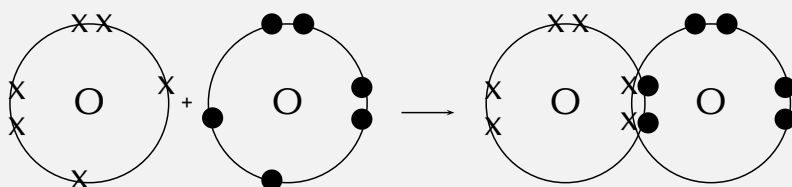
Step 1 : ***Determine the electron configuration of the bonding atoms.***

Each oxygen atom has eight electrons, and their electron configuration is [He]$2s^2 2p^4$.

Step 2 : ***Determine the number of valence electrons for each atom and how many of these electrons are paired and unpaired.***

Each oxygen atom has six valence electrons. Each atom has two unpaired electrons.

Step 3 : ***Work out how the electrons are shared***

Each oxygen atom needs two more electrons to complete its valence energy shell. Therefore *two pairs of electrons* must be shared between the two oxygen atoms so that both outermost energy levels are full. A double bond is formed.

Properties of covalent compounds

ESABV

Covalent compounds have several properties that distinguish them from ionic compounds and metals. These properties are:

1. The melting and boiling points of covalent compounds are generally lower than those of ionic compounds.
2. Covalent compounds are generally more flexible than ionic compounds. The molecules in covalent compounds are able to move around to some extent and can sometimes slide over each other (as is the case with graphite, which is why the lead in your pencil feels slightly slippery). In ionic compounds, all the ions are tightly held in place.
3. Covalent compounds generally are not very soluble in water, for example plastics are covalent compounds and many plastics are water resistant.
4. Covalent compounds generally do not conduct electricity when dissolved in water, for example iodine dissolved in pure water does not conduct electricity.

Exercise 6 - 2

1. Explain the difference between the *valence electrons* and the *valency* of an element.

2. Complete the table below by filling in the number of valence electrons for each of the elements shown:

Element	**Group number**	**No. of valence electrons**	**No. of electrons needed to fill outer shell**
He			
Li			
B			
C			
F			
Ne			
Na			
Al			
P			
S			
Ca			
Kr			

3. Draw simple diagrams to show how electrons are arranged in the following covalent molecules:
   a. hydrogen sulphide (H_2S)
   b. chlorine (Cl_2)
   c. nitrogen (N_2)
   d. carbon monoxide (CO)

More practice video solutions or help at www.everythingscience.co.za

(1.) 0025 (2.) 0026 (3.) 0027

Ionic bonding ESABW

The nature of the ionic bond ESABX

When electrons are *transferred* from one atom to another it is called **ionic bonding**.

Electronegativity is a property of an atom, describing how strongly it attracts or holds onto electrons. Ionic bonding takes place when the difference in electronegativity between the two atoms is more than 1.7. This usually happens when a metal atom bonds with a non-metal atom. When the difference in electronegativity is large, one atom will attract the shared electron pair much more strongly than the other, causing electrons to be transferred to the atom with higher electronegativity. When ionic bonds form, a metal donates one or more electrons, due to having a low electronegativity, to form a positive ion or cation. The non-metal atom has a high electronegativity, and therefore readily gains electrons to form a negative ion or anion. The two ions are then attracted to each other by electrostatic forces.

See video: VPaxl at www.everythingscience.co.za

DEFINITION: Ionic bond

An ionic bond is a type of chemical bond where one or more electrons are transferred from one atom to another.

Example 1:

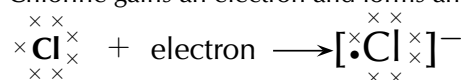
In the case of NaCl, the difference in electronegativity between Na (0,93) and Cl (3,16) is $2,1$. Sodium has only one valence electron, while chlorine has seven. Because the electronegativity of chlorine is higher than the electronegativity of sodium, chlorine will attract the valence electron of the sodium atom very strongly. This electron from sodium is transferred to chlorine. Sodium loses an electron and forms an Na^+ ion.

Note

Chlorine is a diatomic molecule and so for it to take part in ionic bonding, it must first break up into two atoms of chlorine. Sodium is part of a metallic lattice and the individual atoms must first break away from the lattice.

$Na\bullet \longrightarrow Na^+ + \text{electron}$

Chlorine gains an electron and forms an Cl^- ion.

Cl + electron $\longrightarrow [Cl]^-$

The electron is therefore transferred from sodium to chlorine:

$$Na^+ + [Cl]^- \longrightarrow [Na]^+[Cl]^-$$

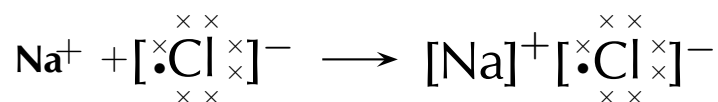
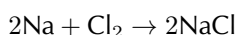



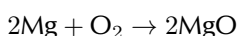
Figure 6.2: Ionic bonding in sodium chloride

The balanced equation for the reaction is:

$$2Na + Cl_2 \rightarrow 2NaCl$$

Example 2:

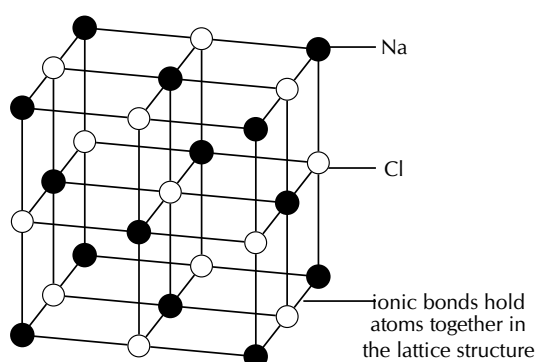
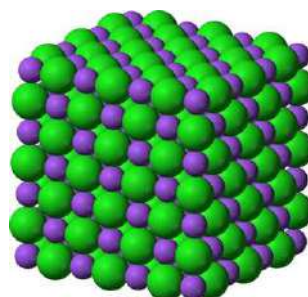
Another example of ionic bonding takes place between magnesium (Mg) and oxygen (O_2) to form magnesium oxide (MgO). Magnesium has two valence electrons and an electronegativity of $1,31$, while oxygen has six valence electrons and an electronegativity of $3,44$. Since oxygen has a higher electronegativity, it attracts the two valence electrons from the magnesium atom and these electrons are transferred from the magnesium atom to the oxygen atom. Magnesium loses two electrons to form Mg^{2+}, and oxygen gains two electrons to form O^{2-}. The attractive force between the oppositely charged ions is what holds the compound together.

The balanced equation for the reaction is:

$$2Mg + O_2 \rightarrow 2MgO$$

Because oxygen is a diatomic molecule, two magnesium atoms will be needed to combine with one oxygen molecule (which has two oxygen atoms) to produce two units of magnesium oxide (MgO).

The crystal lattice structure of ionic compounds

ESABY

Ionic substances are actually a combination of lots of ions bonded together into a giant molecule. The arrangement of ions in a regular, geometric structure is called a **crystal lattice**. So in fact NaCl does not contain one Na and one Cl ion, but rather a lot of these two ions arranged in a crystal lattice where the ratio of Na to Cl ions is 1:1. The structure of the crystal lattice is shown below.

The crystal lattice arrangement in NaCl

A space filling model of the sodium chloride lattice

Properties of Ionic Compounds

ESABZ

Ionic compounds have a number of properties:

1. Ions are arranged in a lattice structure
2. Ionic solids are crystalline at room temperature
3. The ionic bond is a strong electrostatic attraction. This means that ionic compounds are often hard and have high melting and boiling points
4. Ionic compounds are brittle and bonds are broken along planes when the compound is put under pressure (stressed)
5. Solid crystals do not conduct electricity, but ionic solutions do

Exercise 6 - 3

1. Explain the difference between a *covalent* and an *ionic* bond.

2. Magnesium and chlorine react to form magnesium chloride.
   a. What is the difference in electronegativity between these two elements?
   b. Give the chemical formula for:
      i. a magnesium ion
      ii. a chloride ion
      iii. the ionic compound that is produced during this reaction
   c. Write a balanced chemical equation for the reaction that takes place.
3. Draw Lewis diagrams to represent the following ionic compounds:
   a. sodium iodide (NaI)
   b. calcium bromide ($CaBr_2$)
   c. potassium chloride (KCl)

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(1.) 0028 (2.) 0029 (3.) 002a

Metallic Bonding

ESACA

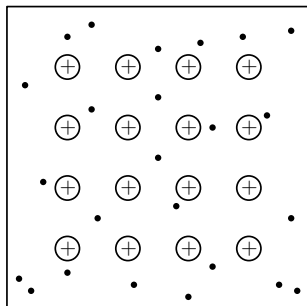
The nature of the metallic bond

ESACB

The structure of a metallic bond is quite different from covalent and ionic bonds. In a metallic bond, the valence electrons are *delocalised*, meaning that an atom's electrons do not stay around that one nucleus. In a metallic bond, the positive atomic nuclei (sometimes called the "atomic kernels") are surrounded by a sea of delocalised electrons which are attracted to the nuclei (see figure below).

See video: VPaxw at www.everythingscience.co.za

DEFINITION: Metallic bond

Metallic bonding is the electrostatic attraction between the positively charged atomic nuclei of metal atoms and the delocalised electrons in the metal.

Positive atomic nuclei (+) surrounded by delocalised electrons (•)

Ball and stick model of copper

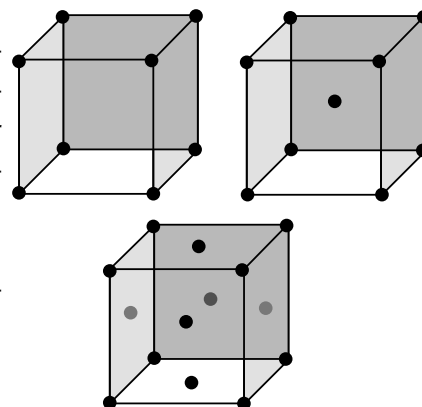
Properties of metals

ESACC

1. Metals are *shiny*.
2. Metals *conduct electricity* because electrons are free to move.
3. Metals *conduct heat* because the positive nuclei are packed closely together and can easily transfer the heat.
4. Metals have a *high melting point* because the bonds are strong and a *high density* because of the tight packing of the nuclei.

Activity:	*Building models*

Using coloured balls (or jellytots) and sticks (or toothpicks) build models of each type of bonding. Think about how to represent each kind of bonding. For example, covalent bonding could be represented by simply connecting the balls with sticks to represent the molecules, while for ionic bonding you may wish to construct part of the crystal lattice.

Do some research on types of crystal lattices (although the section on ionic bonding only showed the crystal lattice for sodium chloride, many other types of lattices exist) and try to build some of these. Share your findings with your class and compare notes to see what types of crystal lattices they found. How would you show metallic bonding?

Exercise 6 - 4

1. Give two examples of everyday objects that contain:
   a. covalent bonds
   b. ionic bonds
   c. metallic bonds
2. Complete the table which compares the different types of bonding:

	Covalent	Ionic	Metallic
Types of atoms involved			
Nature of bond between atoms			
Melting point (high/low)			
Conducts electricity? (yes/no)			
Other properties			

3. Complete the table below by identifying the type of bond (covalent, ionic or metallic) in each of the compounds:

Molecular formula	Type of bond
H_2SO_4	
FeS	
NaI	
$MgCl_2$	
Zn	

4. Use your knowledge of the different types of bonding to explain the following statements:
   a. A sodium chloride crystal does not conduct electricity.
   b. Most jewellery items are made from metals.
   c. It is very hard to break a diamond.
   d. Pots are made from metals, but their handles are made from plastic.

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(1.) 002b (2.) 002c (3.) 002d (4.) 002e

Writing formulae

In chapter 2 you learnt about the writing of chemical formulae. Table 6.2 shows some of the common anions and cations that you should know.

Name of compound ion	formula	Name of compound ion	formula
Acetate (ethanoate)	CH_3COO^-	Manganate	MnO_4^{2-}
Ammonium	NH_4^+	Nitrate	NO_3^-
Carbonate	CO_3^{2-}	Nitrite	NO_2^-
Chlorate	ClO_3^-	Oxalate	$C_2O_4^{2-}$
Chromate	CrO_4^{2-}	Oxide	O^{2-}
Cyanide	CN^-	Permanganate	MnO_4^-
Dihydrogen phosphate	$H_2PO_4^-$	Peroxide	O_2^{2-}
Hydrogen carbonate	HCO_3^-	Phosphate	PO_4^{3-}
Hydrogen phosphate	HPO_4^{3-}	Phosphide	P^{3-}
Hydrogen sulphate	HSO_4^-	Sulphate	SO_4^{2-}
Hydrogen sulphite	HSO_3^-	Sulphide	S^{2-}
Hydroxide	OH^-	Sulphite	SO_3^{2-}
Hypochlorite	ClO^-	Thiosulphate	$S_2O_3^{2-}$

Table 6.2: Table showing common compound ions and their formulae

Chemical compounds: names and masses ESACE

In chapter 4 you learnt about atomic masses. In this chapter we have learnt that atoms can combine to form compounds. Molecules are formed when atoms combine through covalent bonding, for example ammonia is a molecule made up of three hydrogen atoms and one nitrogen atom. The **relative molecular mass** (M) of ammonia (NH_3) is:

$$\begin{aligned} M &= \text{relative atomic mass of one nitrogen} + \text{relative atomic mass of three hydrogens} \\ &= 14,0 + 3(1,01) \\ &= 17,03 \end{aligned}$$

One molecule of NH_3 will have a mass of $17,03$ units. When sodium reacts with chlorine to form sodium chloride, we do not get a molecule of sodium chloride, but rather a sodium chloride crystal lattice. Remember that in ionic bonding molecules are not formed. We can also calculate the mass of one unit of such a crystal. We call this a **formula unit** and the mass is called the **formula mass**. The formula mass for sodium chloride is:

$$\begin{aligned} M &= \text{relative atomic mass of one sodium atom} + \text{relative atomic mass of one chlorine atom} \\ &= 23,0 + 35,45 \\ &= 58,45 \end{aligned}$$

The formula mass for NaCl is $58,45$ units.

Exercise 6 - 5

1. Write the chemical formulae for each of the following compounds and calculate the relative molecular mass or formula mass:
   a. hydrogen cyanide
   b. carbon dioxide
   c. sodium carbonate
   d. ammonium hydroxide
   e. barium sulphate
   f. copper (II) nitrate
2. Complete the following table. The cations at the top combine with the anions on the left. The first row is done for you. Also include the names of the compounds formed and the anions.

	Na^{+}	Mg^{2+}	Al^{3+}	NH_4^{+}	H^{+}
Br^{-} **name:**	NaBr sodium bromide	$MgBr_2$ magnesium bromide	$AlBr_3$ aluminium bromide	$(NH_4)Br$ ammonium bromide	HBr hydrogen bromide
S^{2-} **name:**					
P^{3-} **name:**					
MnO_4^{-} **name:**					
$Cr_2O_7^{2-}$ **name:**					
HPO_4^{2-} **name:**					

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(1.) 002f (2.) 002g

Chapter 6 | Summary

See the summary presentation (Presentation: VPduz at www.everythingscience.co.za)

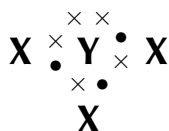
- A **chemical bond** is the physical process that causes atoms and molecules to be attracted to each other and held together in more stable chemical compounds.
- Atoms are more **reactive**, and therefore more likely to bond, when their outer electron orbitals are not full. Atoms are less reactive when these outer orbitals contain the maximum number of electrons. This explains why the noble gases do not react.
- **Lewis** notation is one way of representing molecular structure. In Lewis notation, dots and crosses are used to represent the valence electrons around the central atom.
- When atoms bond, electrons are either shared or exchanged.

- **Covalent bonding** occurs between the atoms of non-metals and involves a sharing of electrons so that the orbitals of the outermost energy levels in the atoms are filled.
- A **double** or **triple bond** occurs if there are two or three electron pairs that are shared between the same two atoms.
- The **valency** is the number of electrons in the outer shell of an atom which are able to be used to form bonds with other atoms.
- Covalent compounds have lower melting and boiling points than ionic compounds. Covalent compounds are also generally flexible, are generally not soluble in water and do not conduct electricity.
- An **ionic bond** occurs between atoms where there is a large difference in electronegativity. An exchange of electrons takes place and the atoms are held together by the electrostatic force of attraction between the resulting oppositely-charged ions.
- Ionic solids are arranged in a **crystal lattice** structure.
- Ionic compounds have high melting and boiling points, are brittle in nature, have a lattice structure and are able to conduct electricity when in solution.
- A **metallic bond** is the electrostatic attraction between the positively charged nuclei of metal atoms and the delocalised electrons in the metal.
- Metals are able to conduct heat and electricity, they have a metallic lustre (shine), they are both malleable (flexible) and ductile (stretchable) and they have a high melting point and density.
- We can work out the relative molecular mass for covalent compounds and the formula mass for ionic compounds and metals.

Chapter 6 End of chapter exercises

1. Explain the meaning of each of the following terms
   a. ionic bond
   b. covalent bond
2. Which ONE of the following best describes the bond formed between carbon and hydrogen?
   a. metallic bond
   b. covalent bond
   c. ionic bond
3. Which of the following reactions will *not* take place? Explain your answer.
   a. $H + H \rightarrow H_2$
   b. $Ne + Ne \rightarrow Ne_2$
   c. $Cl + Cl \rightarrow Cl_2$
4. Draw the Lewis structure for each of the following:

a. calcium
b. iodine
c. hydrogen bromide (HBr)
d. nitrogen dioxide (NO_2)

5. Given the following Lewis structure, where X and Y each represent a different element:

a. What is the valency of X?
b. What is the valency of Y?
c. Which elements could X and Y represent?

6. Complete the following table:

	K^+	Ca^{2+}	NH_4^+
OH^-			
O^{2-}			
NO_3^-			
PO_4^{3-}			

7. Potassium dichromate is dissolved in water.
a. Give the name and chemical formula for each of the ions in solution.
b. What is the chemical formula for potassium dichromate?

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(1.) 002h (2.) 002i (3.) 002j (4.) 002k (5.) 002m (6.) 002n
(7.) 002p

Transverse pulses 7

Introduction and key concepts

This chapter forms the basis of the discussion into mechanical waves in the following chapters. We begin by discussing pulses. Pulses are disturbances in a medium. If you tap water in a bucket with your finger, notice that a ripple moves away from the point where you touched the water. The ripple is a pulse moving away from where you touched the water. See introductory video: (Video: VPchw at www.everythingscience.co.za)

What is a medium?

A medium is the substance or material through which a pulse moves. The medium carries the pulse from one place to another. The medium does not create the pulse and the medium is not the pulse. Therefore the medium does not travel with the pulse as the pulse moves through it.

In each medium, the particles that make up the medium are moved *temporarily* from their rest position. In order for a pulse to travel, the different parts of the medium must be able to interact with each other.

A disturbance in water

Picture by mikeyskatie on Flickr.com

> *DEFINITION: Medium*
>
> A medium is the substance or material in which a pulse will move.

Pulses: amplitude and length

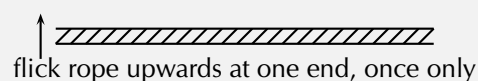
ESACH

What is a pulse?

ESACI

Investigation: Observation of pulses

Take a heavy rope. Have two people hold the rope stretched out horizontally. Flick the rope at one end only once.

flick rope upwards at one end, once only

What happens to the disturbance that you created in the rope? Does it stay at the place where it was created or does it move down the length of the rope?

In the activity, we created a *pulse*. A pulse is a *single* disturbance that moves through a medium. In a transverse pulse the displacement of the medium is perpendicular to the direction of motion of the pulse. Figure 7.2 shows an example of a transverse pulse. In the activity, the rope or spring was held horizontally and the pulse moved the rope up and down. This was an example of a transverse pulse.

DEFINITION: Pulse

A pulse is a single disturbance that moves through a medium.

DEFINITION: Transverse Pulse

A pulse where all of the particles disturbed by the pulse move perpendicular (at a right angle) to the direction in which the pulse is moving.

Pulse length and amplitude

The amplitude of a pulse is a measurement of how far the medium is displaced momentarily from a position of rest. The pulse length is a measurement of how long the pulse is. Both these quantities are shown in Figure 7.2.

DEFINITION: Amplitude

The amplitude of a pulse is the maximum disturbance or distance the medium is displaced from its rest (equilibrium) position.

Quantity: Amplitude (A) Unit name: metre Unit symbol: m

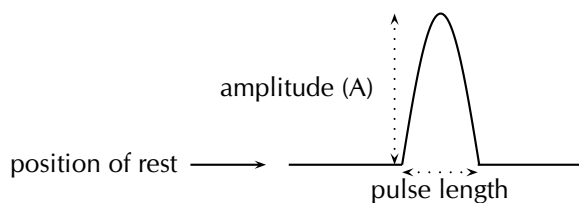
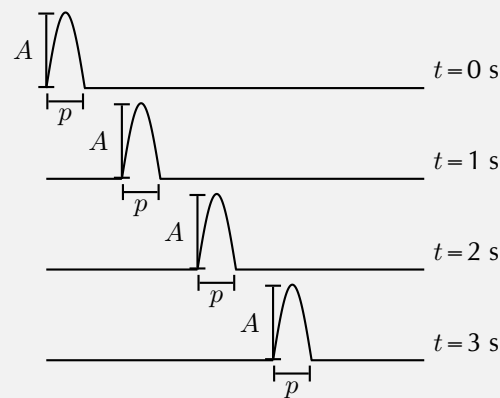



Figure 7.2: Example of a transverse pulse

The position of rest is the position the medium would be in if it were undisturbed. This is also called the equilibrium position. People will often use rest and equilibrium interchangeably.

Investigation: *Pulse length and amplitude*

The graphs below show the positions of a pulse at different times.

Use your ruler to measure the lengths of a and p. Fill your answers in the table.

Sign	**Symbol**	**Meaning**
Sign	**Symbol**	**Meaning**
Time	A	p
$t = 0$ s		
$t = 1$ s		
$t = 2$ s		
$t = 3$ s		

What do you notice about the values of A and p?

In the activity, we found that the values for how high the pulse (A) is and how wide the pulse (p) is the same at different times. *Pulse length* and *amplitude* are two important quantities of a pulse.

Pulse speed

DEFINITION: Pulse speed

Pulse speed is the distance a pulse travels per unit time.
Quantity: Pulse speed (v) Unit name: metre per second Unit symbol: $\text{m} \cdot \text{s}^{-1}$

Speed is defined as the distance travelled per unit time (this will be covered in more detail in Motion in One Dimension). If the pulse travels a distance D in a time t, then the pulse speed v is:

$$\boxed{v = \frac{D}{t}}$$

Example 1: Pulse speed

QUESTION

A pulse covers a distance of 2 m in 4 s on a heavy rope. Calculate the pulse speed.

SOLUTION

Step 1 : ***Analyse the question***

We are given:

- the distance travelled by the pulse: $D = 2\,\text{m}$
- the time taken to travel $2\,\text{m}$: $t = 4\,\text{s}$

We are required to calculate the speed of the pulse.

Step 2 : ***Apply the relevant principles***

We can use:

$$v = \frac{D}{t}$$

to calculate the speed of the pulse.

Step 3 : ***Do the calculation***

$$\begin{aligned} v &= \frac{D}{t} \\ &= \frac{2\ \text{m}}{4\ \text{s}} \\ &= 0,5\ \text{m}\cdot\text{s}^{-1} \end{aligned}$$

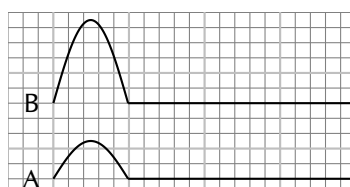
Step 4 : ***Quote the final result***

The pulse speed is $0,5\ \text{m}\cdot\text{s}^{-1}$.

Tip

The pulse speed depends on the properties of the medium and not on the amplitude or pulse length of the pulse.

Exercise 7 - 1

1. A pulse covers a distance of 5 m in 15 s. Calculate the speed of the pulse.
2. A pulse has a speed of $5\ \text{cm}\cdot\text{s}^{-1}$. How far does it travel in $2,5$ s?
3. A pulse has a speed of $0,5\ \text{m}\cdot\text{s}^{-1}$. How long does it take to cover a distance of 25 cm?
4. How long will it take a pulse moving at $0,25\ \text{m}\cdot\text{s}^{-1}$ to travel a distance of 20 m?
5. The diagram shows two pulses in the same medium. Which has the higher speed? Explain your answer.

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(1.) 002q (2.) 002r (3.) 002s (4.) 002t (5.) 002u

Superposition of pulses

ESACJ

See video: VPciu at www.everythingscience.co.za

Two or more pulses can pass through the same medium at that same time in the same place. When they do they interact with each other to form a different disturbance at that point. The resulting pulse is obtained by using the *principle of superposition*.

> ### *DEFINITION: Principle of superposition*
>
> The principle of superposition states that when two disturbance occupy the same space at the same time the resulting disturbance is the sum of two disturbances.

After pulses pass through each other, each pulse continues along its original direction of travel, and their original amplitudes remain unchanged.

Constructive interference takes place when two pulses meet each other to create a larger pulse. The amplitude of the resulting pulse is the sum of the amplitudes of the two initial pulses. This could be two crests meeting or two troughs meeting. This is shown in Figure 7.3.

> ### *DEFINITION: Constructive interference*
>
> Constructive interference is when two pulses meet, resulting in a bigger pulse.

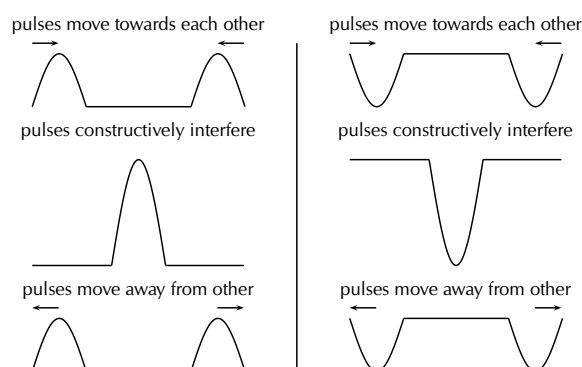



Figure 7.3: Superposition of two pulses: constructive interference.

Destructive interference takes place when two pulses meet and result in a smaller amplitude disturbance. The amplitude of the resulting pulse is the sum of the amplitudes of the two initial pulses, but the one amplitude will be a negative number. This is shown in Figure 7.4. In general, amplitudes of individual pulses are summed together to give the amplitude of the resultant pulse.

DEFINITION: Destructive interference

Destructive interference is when two pulses meet, resulting in a smaller pulse.

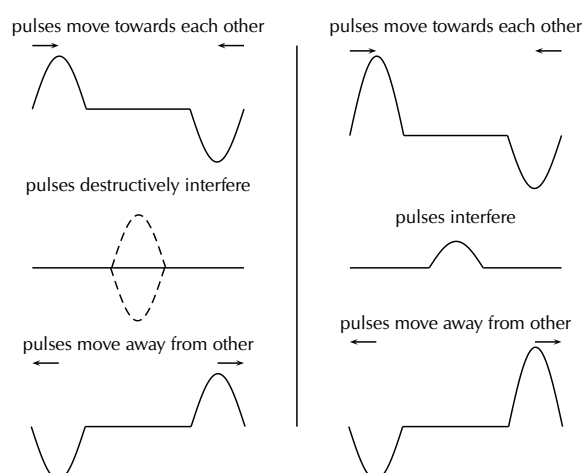
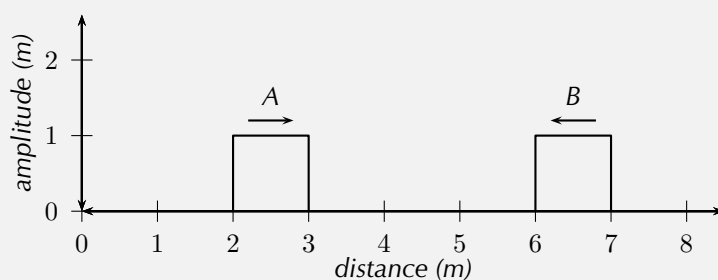



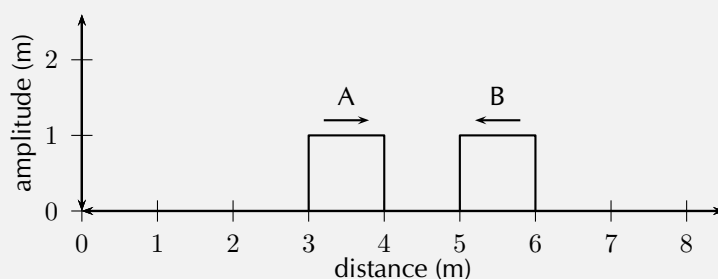
Figure 7.4: Superposition of two pulses. The left-hand series of images demonstrates destructive interference, since the pulses cancel each other. The right-hand series of images demonstrate a partial cancellation of two pulses, as their amplitudes are not the same in magnitude.

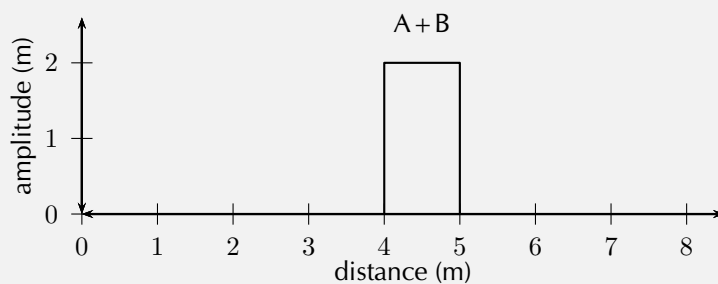
Example 2: *Superposition of pulses*

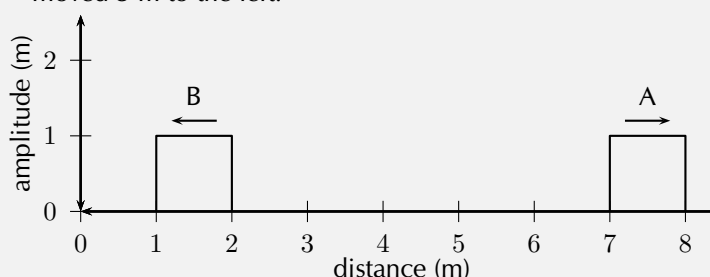
QUESTION

The two pulses shown below approach each other at 1 m · s^{-1}. Draw what the waveform would look like after 1 s, 2 s and 5 s.

SOLUTION

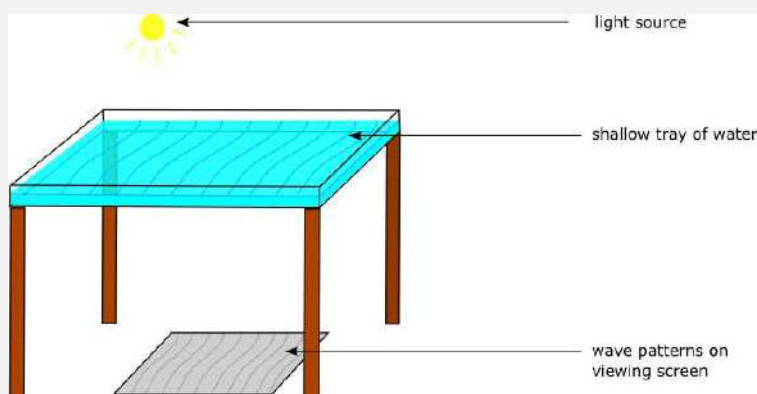
Step 1 : ***After 1 s***

After 1 s, pulse A has moved 1 m to the right and pulse B has moved 1 m to the left.

Step 2 : ***After 2 s***

After 1 s more, pulse A has moved 1 m to the right and pulse B has moved 1 m to the left.

Step 3 : ***After 5 s***

After 5 s more, pulse A has moved 5 m to the right and pulse B has moved 5 m to the left.

General experiment: *Constructive and destructive interference*

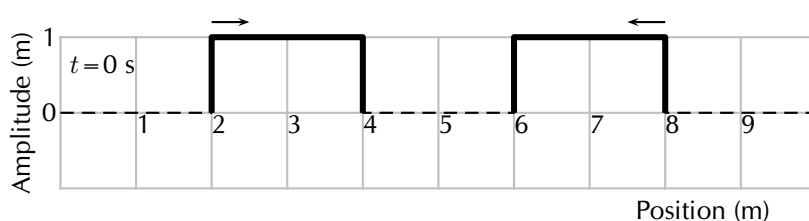
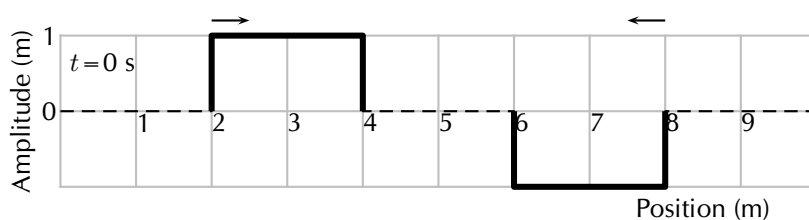
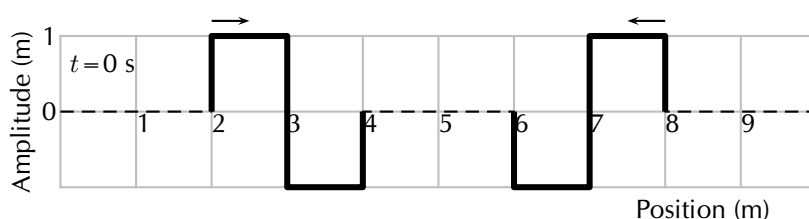
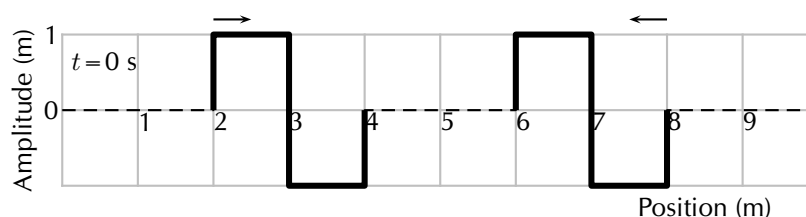
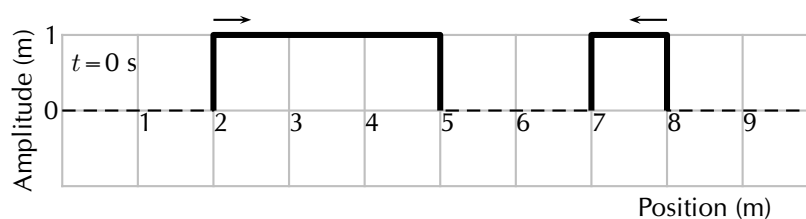
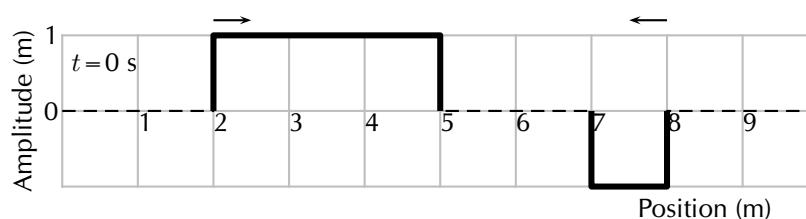
Aim: To demonstrate constructive and destructive interference

Apparatus: Ripple tank apparatus

Method:

1. Set up the ripple tank
2. Produce a single pulse and observe what happens (you can do this any means, tapping the water with a finger, dropping a small object into the water, tapping a ruler or even using a electronic vibrator)
3. Produce two pulses simultaneously and observe what happens
4. Produce two pulses at slightly different times and observe what happens

Results and conclusion: You should observe that when you produce two pulses simultaneously you see them interfere constructively and when you produce two pulses at slightly different times you see them interfere destructively.

Exercise 7 - 2

1. For the following pulse, draw the resulting wave forms after 1 s, 2 s, 3 s, 4 s and 5 s. Each pulse is travelling at 1 m$\cdot$s^{-1}. Each block represents 1 m. The pulses are shown as thick black lines and the undisplaced medium as dashed lines.

2. For the following pulse, draw the resulting wave forms after 1 s, 2 s, 3 s, 4 s and 5 s. Each pulse is travelling at 1 m$\cdot$s^{-1}. Each block represents 1 m. The pulses are shown as thick black lines and the undisplaced medium as dashed lines.

3. For the following pulse, draw the resulting wave forms after 1 s, 2 s, 3 s, 4 s and 5 s. Each pulse is travelling at 1 m$\cdot$s^{-1}. Each block represents 1 m. The pulses are shown as thick black lines and the undisplaced medium as dashed lines.

4. For the following pulse, draw the resulting wave forms after 1 s, 2 s, 3 s, 4 s and 5 s. Each pulse is travelling at 1 m·s^{-1}. Each block represents 1 m. The pulses are shown as thick black lines and the undisplaced medium as dashed lines.

5. For the following pulse, draw the resulting wave forms after 1 s, 2 s, 3 s, 4 s and 5 s. Each pulse is travelling at 1 m·s^{-1}. Each block represents 1 m. The pulses are shown as thick black lines and the undisplaced medium as dashed lines.

6. For the following pulse, draw the resulting wave forms after 1 s, 2 s, 3 s, 4 s and 5 s. Each pulse is travelling at 1 m·s^{-1}. Each block represents 1 m. The pulses are shown as thick black lines and the undisplaced medium as dashed lines.

7. What is superposition of waves?

8. What is constructive interference?

9. What is destructive interference?

More practice video solutions or help at www.everythingscience.co.za

(1.) 002v (2.) 002w (3.) 002x (4.) 002y (5.) 002z (6.) 0030
(7.) 0031 (8.) 0032 (9.) 0033

Chapter 7 | Summary

See the summary presentation (Presentation: VPcjo at www.everythingscience.co.za)

- A medium is the substance or material in which a pulse will move.
- A pulse is a single disturbance that moves through a medium.
- The amplitude of a pulse is the maximum disturbance or distance the medium is displaced from its equilibrium position (rest).
- Pulse speed is the distance a pulse travels per unit time.
- Constructive interference is when two pulses meet and result in a bigger pulse.
- Destructive interference is when two pulses meet and and result in a smaller pulse.

Physical Quantities		
Quantity	**Unit name**	**Unit symbol**
Amplitude (A)	metre	m
Pulse speed (v)	metre per second	$m \cdot s^{-1}$

Table 7.1: Units used in **transverse pulses**

Chapter 7 End of chapter exercises

1. A heavy rope is flicked upwards, creating a single pulse in the rope. Make a drawing of the rope and indicate the following in your drawing:
   a. The direction of motion of the pulse

b. Amplitude
   c. Pulse length
   d. Position of rest
2. A pulse has a speed of $2,5\text{ m}\cdot\text{s}^{-1}$. How far will it have travelled in 6 s?

3. A pulse covers a distance of 75 cm in $2,5\text{ s}$. What is the speed of the pulse?

4. How long does it take a pulse to cover a distance of 200 mm if its speed is $4\text{ m}\cdot\text{s}^{-1}$?

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(1.) 0034 (2.) 0035 (3.) 0036 (4.) 0037

Transverse waves

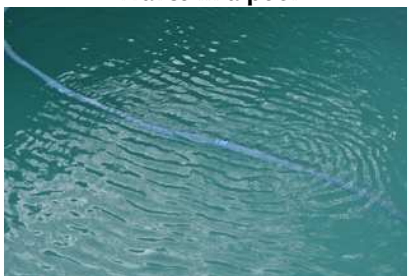
8

Introduction

Waves occur frequently in nature. The most obvious examples are waves in water, on a dam, in the ocean, or in a bucket. We are interested in the properties that waves have. All waves have the same properties.

Waves do not only occur in water, they occur in any kind of medium. Earthquakes release enough energy to create waves that are powerful enough to travel through the rock of the Earth. When your friend speaks to you *sound waves* are produced that travel through the air to your ears. A wave is simply the disturbance of a medium by moving energy but how is it different from a pulse?. See introductory video: (Video: VPgio at www.everythingscience.co.za)

What is a transverse wave?

Waves in a pool

We have studied pulses in *Transverse pulses*, and know that a pulse is a single disturbance that travels through a medium. A *wave* is a periodic, continuous disturbance that consists of a *train* or *succession* of pulses.

An enlarged version of the ripple tank can be seen in a real life example of a Kreepy Krauly® making waves in a pool because of the regular vibrations. The Kreepy Krauly® was invented in South Africa by Ferdinand Chauvier and his son Daniel.

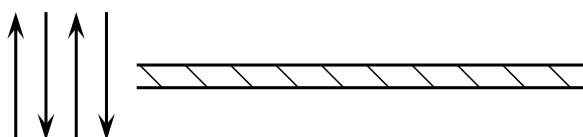
DEFINITION: Wave

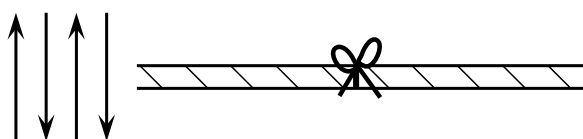
A *wave* is a periodic, continuous disturbance that consists of a *train* of pulses.

DEFINITION: Transverse wave

A *transverse wave* is a wave where the movement of the particles of the medium is perpendicular (at a right angle) to the direction of propagation of the wave.

Activity: *Transverse waves*

Take a rope or slinky spring. Have two people hold the rope or spring stretched out horizontally. Flick the one end of the rope up and down **continuously** to create a *train of pulses*.

Flick rope up and down

1. Describe what happens to the rope.
2. Draw a diagram of what the rope looks like while the pulses travel along it.
3. In which direction do the pulses travel?
4. Tie a ribbon to the middle of the rope. This indicates a particle in the rope.

Flick rope up and down

5. Flick the rope continuously. Watch the ribbon carefully as the pulses travel through the rope. What happens to the ribbon?
6. Draw a picture to show the motion of the ribbon. Draw the ribbon as a dot and use arrows to indicate how it moves.

In the activity, you created waves. The medium through which these waves propagated was the rope, which is obviously made up of a very large number of particles (atoms). From the activity, you would have noticed that the wave travelled from one side to the other, but the particles (the ribbon) moved only up and down.

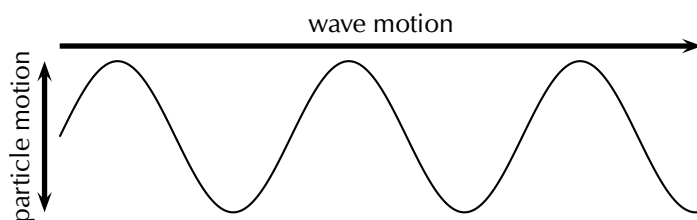



Figure 8.2: A transverse wave, showing the direction of motion of the wave perpendicular to the direction in which the particles move.

When the particles of a medium move at right angles to the direction of propagation of a wave, the wave is called *transverse*. For waves, there is no net displacement of the particles of the medium (they return to their equilibrium position), but there is a net displacement of the wave. There are thus two different motions: the motion of the particles of the medium and the motion of the wave.

The following simulation will help you understand more about waves. Select the oscillate option and then observe what happens. See simulation: (▶ Simulation: VPnue at www.everythingscience.co.za)

Crests and troughs

ESACM

Waves have moving *crests* (or *peaks*) and *troughs*. A crest is the highest point the medium rises to and a trough is the lowest point the medium sinks to.

crests and troughs on a transverse wave are shown in Figure 8.3.

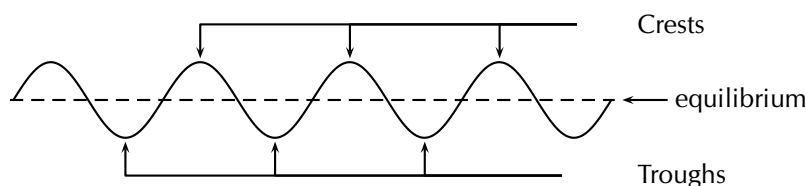
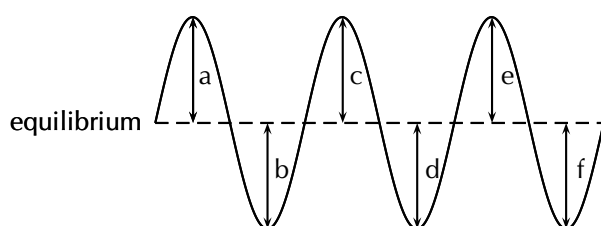



Figure 8.3: Crests and troughs in a transverse wave.

> ## *DEFINITION: Crests and troughs*
>
> A *crest* is a point on the wave where the displacement of the medium is at a maximum. A point on the wave is a *trough* if the displacement of the medium at that point is at a minimum.

Amplitude

ESACN

Activity:	*Amplitude*

Fill in the table below by measuring the distance between the equilibrium and each crest and trough in the wave above. Use your ruler to measure the distances.

Crest/Trough	Measurement (cm)
a	
b	
c	
d	
e	
f	

1. What can you say about your results?
2. Are the distances between the equilibrium position and each crest equal?
3. Are the distances between the equilibrium position and each trough equal?
4. Is the distance between the equilibrium position and crest equal to the distance between equilibrium and trough?

As we have seen in the activity on amplitude, the distance between the crest and the equilibrium position is equal to the distance between the trough and the equilibrium position. This distance is known as the *amplitude* of the wave, and is the characteristic height of the wave, above or below the equilibrium position. Normally the symbol A is used to represent the amplitude of a wave. The SI unit of amplitude is the metre (m).

DEFINITION: Amplitude

The amplitude of a wave is the maximum disturbance or displacement of the medium from the equilibrium (rest) position.

Quantity: Amplitude (A) Unit name: metre Unit symbol: m

FACT

A tsunami is a series of sea waves caused by an underwater earthquake, landslide, or volcanic eruption. When the ocean is deep, tsunamis may be less than 30 cm high on the ocean's surface and can travel at speeds up to 700 km · hr^{-1}. In shallow water near the coast, it slows down. The top of the wave moves faster than the bottom, causing the sea to rise dramatically, as much as 30 m. The wavelength can be as long as 100 km and the period as long as a hour.

In 2004, the Indian Ocean tsunami was caused by an earthquake that is thought to have had the energy of 23,000 atomic bombs. Within hours of the earthquake, killer waves radiating from away from the earthquake crashed into the coastline of 11 countries, killing 150,000 people. The final death toll was 283,000.

Example 1: *Amplitude of sea waves*

QUESTION

If the crest of a wave measures 2 m above the still water mark in the harbour, what is the amplitude of the wave?

SOLUTION

Step 1 : ***Analyse the information provided***

We have been told that the harbour has a still water mark. This is a line created when there are no disturbances in the water, which means that it is the equilibrium position of the water.

Step 2 : ***Determine the amplitude***

The definition of the amplitude is the height of a crest above the equilibrium position. The still water mark is the height of the water at equilibrium and the crest is 2 m above this, so the amplitude is 2 m.

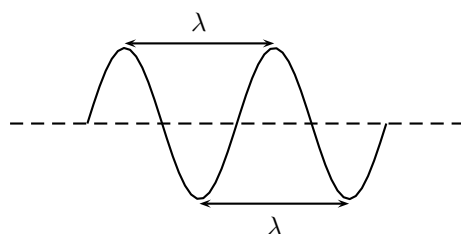
Activity:	*Wavelength*

Fill in the table below by measuring the distance between crests and troughs in the wave above.

	Distance(cm)
a	
b	
c	
d	

1. What can you say about your results?
2. Are the distances between crests equal?
3. Are the distances between troughs equal?
4. Is the distance between crests equal to the distance between troughs?

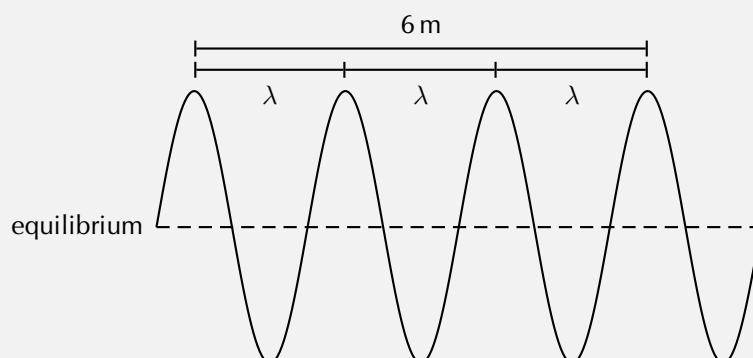
As we have seen in the activity on wavelength, the distance between two *adjacent* crests is the same no matter which two adjacent crests you choose. There is a fixed distance between the crests. Similarly, we have seen that there is a fixed distance between the troughs, no matter which two troughs you look at. More importantly, the distance between two adjacent crests is the same as the distance between two adjacent troughs. This distance is called the *wavelength* of the wave.

The symbol for the wavelength is λ (the Greek letter *lambda*) and wavelength is measured in metres (m).

Example 2: Wavelength

QUESTION

The total distance between 4 consecutive crests of a transverse wave is 6 m. What is the wavelength of the wave?

SOLUTION

Step 1 : ***Draw a rough sketch of the situation***

Step 2 : ***Determine how to approach the problem***

From the sketch we see that 4 consecutive crests is equivalent to 3 wavelengths.

Step 3 : ***Solve the problem***

Therefore, the wavelength of the wave is:

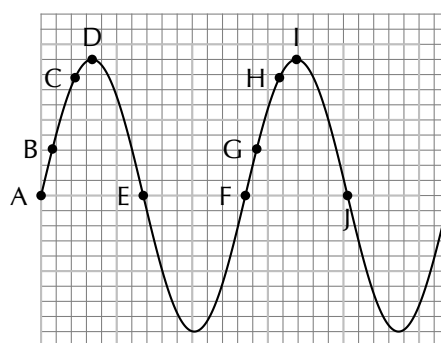
$$\begin{aligned} 3\lambda &= 6 \text{ m} \\ \lambda &= \frac{6 \text{ m}}{3} \\ &= 2 \text{ m} \end{aligned}$$

Step 4 : ***Quote the final answer***

The wavelength is 2 m.

Points in phase

Activity:	*Points in phase*

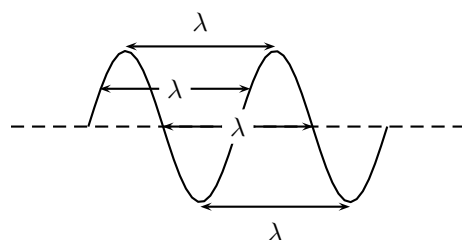
Fill in the table by measuring the distance between the indicated points.

Points	**Distance (cm)**
A to F	
B to G	
C to H	
D to I	
E to J	

What do you find?

In the activity the distance between the indicated points was equal. These points are then said to be *in phase*. Two points in phase are separate by a whole $(1, 2, 3, \ldots)$ number multiple of whole wave cycles or wavelengths. The points in phase do not have to be crests or troughs, but they must be separated by a complete number of wavelengths.

We then have an alternate definition of the wavelength as the distance between any two adjacent points which are *in phase*.

DEFINITION: Wavelength of wave

The wavelength of a wave is the distance between any two adjacent points that are in phase.

Points that are not in phase, those that are not separated by a complete number of wavelengths, are called *out of phase*. Examples of points like these would be A and C, or D and E, or B and H in the Activity.

Period and frequency ESACP

Imagine you are sitting next to a pond and you watch the waves going past you. First one crest arrives, then a trough, and then another crest. Suppose you measure the time taken between one crest arriving and then the next. This time will be the same for any two successive crests passing you. We call this time the *period*, and it is a characteristic of the wave.

The symbol T is used to represent the period. The period is measured in seconds (s).

DEFINITION: Period

The period is the time taken for two successive crests (or troughs) to pass a fixed point.
Quantity: Period (T) Unit name: second Unit symbol: s

Imagine the pond again. Just as a crest passes you, you start your stopwatch and count each crest going past. After 1 second you stop the clock and stop counting. The number of

crests that you have counted in the 1 second is the *frequency* of the wave.

DEFINITION: Frequency

The frequency is the number of successive crests (or troughs) passing a given point in 1 second.

Quantity: Frequency (f) Unit name: hertz Unit symbol: Hz

The frequency and the period are related to each other. As the period is the time taken for 1 crest to pass, then the number of crests passing the point in 1 second is $\frac{1}{T}$. But this is the frequency. So

$$\boxed{f = \frac{1}{T}}$$

or alternatively,

$$\boxed{T = \frac{1}{f}}.$$

For example, if the time between two consecutive crests passing a fixed point is $\frac{1}{2}$ s, then the period of the wave is $\frac{1}{2}$ s. Therefore, the frequency of the wave is:

$$\begin{aligned} f &= \frac{1}{T} \\ &= \frac{1}{\frac{1}{2}\,\text{s}} \\ &= 2\,\text{s}^{-1} \end{aligned}$$

The unit of frequency is the Hertz (Hz) or s^{-1}.

Example 3: Period and frequency

QUESTION

What is the period of a wave of frequency 10 Hz?

SOLUTION

Step 1 : ***Determine what is given and what is required***

We are required to calculate the period of a 10 Hz wave.

Step 2 : ***Determine how to approach the problem***

We know that:

$$T = \frac{1}{f}$$

Step 3 : ***Solve the problem***

$$\begin{aligned} T &= \frac{1}{f} \\ &= \frac{1}{10\,\text{Hz}} \\ &= 0,1\,\text{s} \end{aligned}$$

Step 4 : ***Write the answer***

The period of a 10 Hz wave is 0,1 s.

Speed of a transverse wave

DEFINITION: Wave speed

Wave speed is the distance a wave travels per unit time.
Quantity: Wave speed (v) Unit name: metre per second Unit symbol: $\text{m} \cdot \text{s}^{-1}$

The distance between two successive crests is 1 wavelength, λ. Thus in a time of 1 period, the wave will travel 1 wavelength in distance. Thus the speed of the wave, v, is:

$$\boxed{v = \frac{\text{distance travelled}}{\text{time taken}} = \frac{\lambda}{T}}$$

However, $f = \frac{1}{T}$. Therefore, we can also write:

$$\begin{aligned} v &= \frac{\lambda}{T} \\ &= \lambda \cdot \frac{1}{T} \\ &= \lambda \cdot f \end{aligned}$$

We call this equation the *wave equation*. To summarise, we have that $v = \lambda \cdot f$ where

- v = speed in $\text{m} \cdot \text{s}^{-1}$
- λ = wavelength in m
- f = frequency in Hz

Wave equation

$$\boxed{v = f \cdot \lambda} \quad \text{or} \quad \boxed{v = \frac{\lambda}{T}}$$

Example 4: *Speed of a transverse wave I*

QUESTION

When a particular string is vibrated at a frequency of 10 Hz, a transverse wave of wavelength 0,25 m is produced. Determine the speed of the wave as it travels along the string.

SOLUTION

Step 1 : ***Determine what is given and what is required***

- frequency of wave: $f = 10\,\text{Hz}$
- wavelength of wave: $\lambda = 0{,}25\,\text{m}$

We are required to calculate the speed of the wave as it travels along the string.
All quantities are in SI units.

Step 2 : ***Determine how to approach the problem***

We know that the speed of a wave is:

$$v = f \cdot \lambda$$

and we are given all the necessary quantities.

Step 3 : ***Substituting in the values***

$$\begin{aligned} v &= f \cdot \lambda \\ &= (10 \text{ Hz})(0,25 \text{ m}) \\ &= (10 \text{ s}^{-1})(0,25 \text{ m}) \\ &= 2,5 \text{ m} \cdot \text{s}^{-1} \end{aligned}$$

Step 4 : ***Write the final answer***

The wave travels at 2,5 $\text{m} \cdot \text{s}^{-1}$ along the string.

Example 5: *Speed of a transverse wave II*

QUESTION

A cork on the surface of a swimming pool bobs up and down once every second on some ripples. The ripples have a wavelength of 20 cm. If the cork is 2 m from the edge of the pool, how long does it take a ripple passing the cork to reach the edge?

SOLUTION

Step 1 : ***Determine what is given and what is required***

We are given:

- frequency of wave: $f = 1$ Hz
- wavelength of wave: $\lambda = 20$ cm
- distance of cork from edge of pool: $D = 2$ m

We are required to determine the time it takes for a ripple to travel between the cork and the edge of the pool.
The wavelength is not in SI units and should be converted.

Step 2 : ***Determine how to approach the problem***

The time taken for the ripple to reach the edge of the pool is obtained from:

$$t = \frac{D}{v} \quad (\text{from } v = \frac{D}{t})$$

We know that

$$v = f \cdot \lambda$$

Therefore,

$$t = \frac{D}{f \cdot \lambda} \tag{8.1}$$

Step 3 : ***Convert wavelength to SI units***

$$20\,\text{cm} = 0,2\,\text{m}$$

Step 4 : ***Solve the problem***

$$\begin{aligned} t &= \frac{d}{f \cdot \lambda} \\ &= \frac{2\text{ m}}{(1\text{ Hz})(0,2\text{ m})} \\ &= \frac{2\text{ m}}{(1\text{ s}^{-1})(0,2\text{ m})} \\ &= 10\text{ s} \end{aligned}$$

Step 5 : ***Write the final answer***

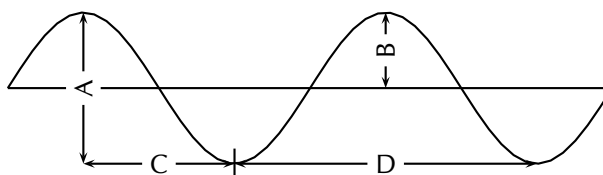
A ripple passing the leaf will take 10 s to reach the edge of the pool.

See video: VPcci at www.everythingscience.co.za

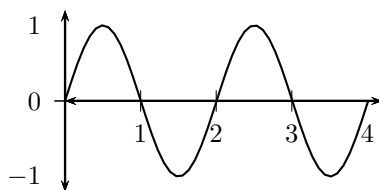
Exercise 8 - 1

1. When the particles of a medium move perpendicular to the direction of the wave motion, the wave is called a .... wave.

2. A transverse wave is moving downwards. In what direction do the particles in the medium move?

3. Consider the diagram below and answer the questions that follow:

a. the wavelength of the wave is shown by letter _________.

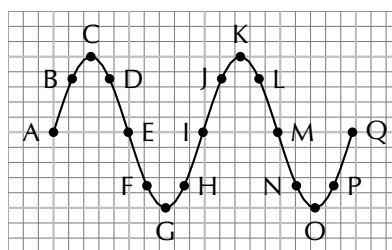
b. the amplitude of the wave is shown by letter _________.

4. Draw 2 wavelengths of the following transverse waves on the same graph paper. Label all important values.
   a. Wave 1: Amplitude = 1 cm, wavelength = 3 cm
   b. Wave 2: Peak to trough distance (vertical) = 3 cm, crest to crest distance (horizontal) = 5 cm
5. You are given the transverse wave below.

Draw the following:
   a. A wave with twice the amplitude of the given wave.
   b. A wave with half the amplitude of the given wave.
   c. A wave travelling at the same speed with twice the frequency of the given wave.
   d. A wave travelling at the same speed with half the frequency of the given wave.
   e. A wave with twice the wavelength of the given wave.
   f. A wave with half the wavelength of the given wave.
   g. A wave travelling at the same speed with twice the period of the given wave.
   h. A wave travelling at the same speed with half the period of the given wave.
6. A transverse wave travelling at the same speed with an amplitude of 5 cm has a frequency of 15 Hz. The horizontal distance from a crest to the nearest trough is measured to be 2,5 cm. Find the
   a. period of the wave.
   b. speed of the wave.
7. A fly flaps its wings back and forth 200 times each second. Calculate the period of a wing flap.

8. As the period of a wave increases, the frequency ***increases/decreases/does not change.***

9. Calculate the frequency of rotation of the second hand on a clock.

10. Microwave ovens produce radiation with a frequency of 2 450 MHz (1 MHz = 10^6 Hz) and a wavelength of 0,122 m. What is the wave speed of the radiation?

11. Study the following diagram and answer the questions:

a. Identify two sets of points that are in phase.
b. Identify two sets of points that are out of phase.
c. Identify any two points that would indicate a wavelength.

12. Tom is fishing from a pier and notices that four wave crests pass by in 8 s and estimates the distance between two successive crests is 4 m. The timing starts with the first crest and ends with the fourth. Calculate the speed of the wave.

More practice video solutions or help at www.everythingscience.co.za

(1.) 0039 (2.) 003a (3.) 003b (4.) 003c (5.) 003d (6.) 003e
(7.) 003f (8.) 003g (9.) 003h (10.) 003i (11.) 003j (12.) 003k

Chapter 8 | Summary

See the summary presentation (Presentation: VPguj at www.everythingscience.co.za)

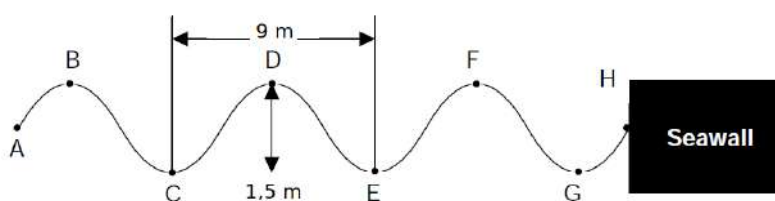
- A wave is formed when a continuous number of pulses are transmitted through a medium.
- A crest is the highest point a particle in the medium rises to.
- A trough is the lowest point a particle in the medium sinks to.
- In a transverse wave, the particles move perpendicular to the motion of the wave.
- The amplitude (A) is the maximum distance from equilibrium position to a crest (or trough), or the maximum displacement of a particle in a wave from its position of rest.

- The wavelength (λ) is the distance between any two adjacent points on a wave that are in phase. It is measured in metres.
- The period (T) of a wave is the time it takes a wavelength to pass a fixed point. It is measured in seconds (s).
- The frequency (f) of a wave is how many waves pass a point in a second. It is measured in hertz (Hz) or s^{-1}.
- Frequency: $f = \frac{1}{T}$
- Period: $T = \frac{1}{f}$
- Speed: $v = f \cdot \lambda$ or $v = \frac{\lambda}{T}$.

Physical Quantities		
Quantity	**Unit name**	**Unit symbol**
Amplitude (A)	metre	m
Wavelength (λ)	metre	m
Period (T)	second	s
Frequency (f)	hertz	Hz (s^{-1})
Wave speed (v)	metre per second	m $\cdot$ s^{-1}

Table 8.1: Units used in **transverse waves**

Chapter 8 End of chapter exercises

1. A wave travels along a string at a speed of $1,5$m $\cdot$ s^{-1}. If the frequency of the source of the wave is 7,5 Hz, calculate:
   a. the wavelength of the wave
   b. the period of the wave
2. Water waves crash against a seawall around the harbour. Eight waves hit the seawall in 5 s. The distance between successive troughs is 9 m. The height of the waveform trough to crest is 1,5 m.

   a. How many complete waves are indicated in the sketch?

b. Write down the letters that indicate any TWO points that are:
   i. in phase
   ii. out of phase
   iii. Represent ONE wavelength.
c. Calculate the amplitude of the wave.
d. Show that the period of the wave is 0,625 s.
e. Calculate the frequency of the waves.
f. Calculate the velocity of the waves.

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(1.) 003m (2.) 003n

Longitudinal waves 9

Introduction and key concepts

ESACR

We have already studied transverse pulses and waves. In this chapter we look at another type of wave called a *longitudinal* wave. In transverse waves, the motion of the particles in the medium was perpendicular to the direction of the wave. In longitudinal waves, the particles in the medium move *parallel* (in the *same* direction as) to the motion of the wave. Examples of transverse waves (discussed in the previous chapter) are water waves. An example of a longitudinal wave is a sound wave. See introductory video: (Video: VPdim at www.everythingscience.co.za)

What is a longitudinal wave?

ESACS

> *DEFINITION: Longitudinal waves*
>
> A longitudinal wave is a wave where the particles in the medium move parallel to the direction of propagation of the wave.

When we studied transverse waves we looked at two different motions: the motion of the particles of the medium and the motion of the wave itself. We will do the same for longitudinal waves.

The question is how do we construct such a wave?

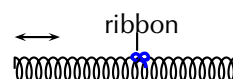
A longitudinal wave is seen best in a slinky spring. Do the following investigation to find out more about longitudinal waves.

Activity:	*Investigating longitudinal waves*

A slinky spring

Photograph by Tim Ebbs on Flickr.com

Take a slinky spring and lay it on a table. Hold one end and pull the free end of the spring and flick it back and forth once in the direction of the spring. Observe what happens.

In which direction does the disturbance move?

Tie a ribbon to the middle of the spring. Watch carefully what happens to the ribbon when the end of the spring is flicked. Describe the motion of the ribbon.

Flick the spring back and forth continuously to set up a train of pulses, a longitudinal wave.

From the investigation you will have noticed that the disturbance moves parallel to the direction in which the spring was pulled. The ribbon in the investigation represents one particle in the medium. The particles in the medium move in the same direction as the wave. See video: VPdkf at www.everythingscience.co.za

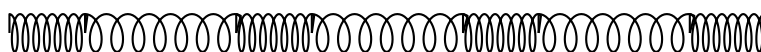
direction of motion of wave

motion of particles in spring is back and forth

Figure 9.2: Longitudinal wave through a spring

As in the case of transverse waves the following properties can be defined for longitudinal waves: wavelength, amplitude, period, frequency and wave speed.

Compression and rarefaction

However instead of crests and troughs, longitudinal waves have *compressions* and *rarefactions*.

DEFINITION: Compression

A **compression** is a region in a longitudinal wave where the particles are closest together.

DEFINITION: Rarefaction

A **rarefaction** is a region in a longitudinal wave where the particles are furthest apart.

See video: VPdml at www.everythingscience.co.za

As seen in Figure 9.3, there are regions where the medium is compressed and other regions where the medium is spread out in a longitudinal wave.

The region where the medium is compressed is known as a **compression** and the region where the medium is spread out is known as a **rarefaction**.

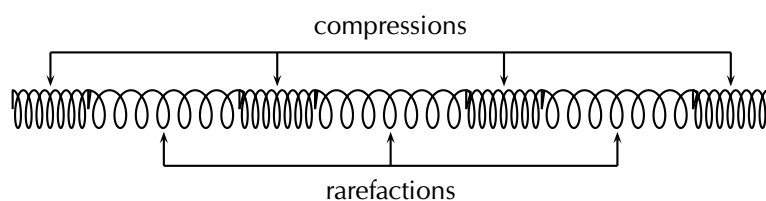



Figure 9.3: Compressions and rarefactions on a longitudinal wave

Wavelength and amplitude

DEFINITION: Wavelength

The **wavelength** in a longitudinal wave is the distance between two consecutive points that are in phase.

The wavelength in a longitudinal wave refers to the distance between two consecutive compressions or between two consecutive rarefactions.

DEFINITION: Amplitude

The **amplitude** is the maximum displacement from equilibrium. For a longitudinal wave which is a pressure wave this would be the maximum increase (or decrease) in pressure from the equilibrium pressure that is cause when a compression (or rarefaction) passes a point.

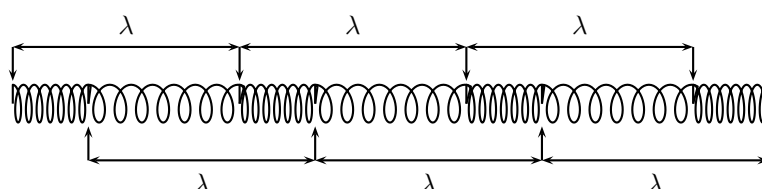



Figure 9.4: Wavelength of a longitudinal wave

The amplitude is the distance from the equilibrium position of the medium to a compression or a rarefaction.

Period and frequency

www ESACV

DEFINITION: Period

The **period** of a wave is the time taken by the wave to move one wavelength.

DEFINITION: Frequency

The **frequency** of a wave is the number of wavelengths per second.

The *period* of a longitudinal wave is the time taken by the wave to move one wavelength. As for transverse waves, the symbol T is used to represent period and period is measured in seconds (s).

The *frequency* f of a wave is the number of wavelengths per second. Using this definition and the fact that the period is the time taken for 1 wavelength, we can define:

$$f = \frac{1}{T}$$

or alternately,

$$T = \frac{1}{f}$$

Speed of a longitudinal wave

ESACW

The speed of a longitudinal wave is defined in the same was as the speed of transverse waves:

DEFINITION: Wave speed

Wave speed is the distance a wave travels per unit time.

Quantity: Wave speed (v) Unit name: speed Unit: m · s^{-1}

The distance between two successive compressions is 1 wavelength, λ. Thus in a time of 1 period, the wave will travel 1 wavelength in distance. Thus the speed of the wave, v, is:

$$v = \frac{\text{distance travelled}}{\text{time taken}} = \frac{\lambda}{T}$$

However, $f = \frac{1}{T}$. Therefore, we can also write:

$$
\begin{aligned}
v &= \frac{\lambda}{T} \\
&= \lambda \cdot \frac{1}{T} \\
&= \lambda \cdot f
\end{aligned}
$$

We call this equation the *wave equation*. To summarise, we have that $v = \lambda \cdot f$ where

- $v =$ speed in $\text{m} \cdot \text{s}^{-1}$
- $\lambda =$ wavelength in m
- $f =$ frequency in Hz

Example 1: *Speed of longitudinal waves*

QUESTION

The musical note "A" is a sound wave. The note has a frequency of 440 Hz and a wavelength of 0,784 m. Calculate the speed of the musical note.

SOLUTION

Step 1 : ***Determine what is given and what is required***

Using:

$$
\begin{aligned}
f &= 440 \text{ Hz} \\
\lambda &= 0,784 \text{ m}
\end{aligned}
$$

We need to calculate the speed of the musical note "A".

Step 2 : ***Determine how to approach based on what is given***

We are given the frequency and wavelength of the note. We can therefore use:

$$v = f \cdot \lambda$$

Step 3 : ***Calculate the wave speed***

$$
\begin{aligned}
v &= f \cdot \lambda \\
&= (440 \text{ Hz})(0,784 \text{ m}) \\
&= 345 \text{ m} \cdot \text{s}^{-1}
\end{aligned}
$$

Step 4 : ***Write the final answer***

The musical note "A" travels at 345 m $\cdot$ s^{-1}.

Example 2: *Speed of longitudinal waves*

QUESTION

A longitudinal wave travels into a medium in which its speed increases. How does this affect its... (write only increases, decreases, stays the same).

1. *period?*

2. *wavelength?*

SOLUTION

Step 1 : ***Determine what is required***

We need to determine how the period and wavelength of a longitudinal wave change when its speed increases.

Step 2 : ***Determine how to approach based on what is given***

We need to find the link between period, wavelength and wave speed.

Step 3 : ***Discuss how the period changes***

We know that the frequency of a longitudinal wave is dependent on the frequency of the vibrations that lead to the creation of the longitudinal wave. Therefore, the frequency is always unchanged, irrespective of any changes in speed. Since the period is the inverse of the frequency, the period remains the same.

Step 4 : ***Discuss how the wavelength changes***

The frequency remains unchanged. According to the wave equation

$$v = f \cdot \lambda$$

if f remains the same and v increases, then λ, the wavelength, must also increase.

Chapter 9 | Summary

See the summary presentation (▶ Presentation: VPduk at www.everythingscience.co.za)

- A longitudinal wave is a wave where the particles in the medium move parallel to the direction in which the wave is travelling.
- Most longitudinal waves consist of areas of higher pressure, where the particles in the medium are closest together (compressions) and areas of lower pressure, where the particles in the medium are furthest apart (rarefactions).
- The wavelength of a longitudinal wave is the distance between two consecutive compressions, or two consecutive rarefactions.
- The relationship between the period (T) and frequency (f) is given by

$$T = \frac{1}{f} \text{ or } f = \frac{1}{T}$$

- The relationship between wave speed (v), frequency (f) and wavelength (λ) is given by

$$v = f\lambda$$

Physical Quantities		
Quantity	**Unit name**	**Unit symbol**
Amplitude (A)	metre	m
Wavelength (λ)	metre	m
Period (T)	second	s
Frequency (f)	hertz	Hz (s^{-1})
Wave speed (v)	metre per second	$\text{m} \cdot \text{s}^{-1}$

Table 9.1: Units used in **longitudinal waves**

Chapter 9 End of chapter exercises

1. Which of the following is not a longitudinal wave?
   a. light
   b. sound
   c. ultrasound
2. Which of the following media can a longitudinal wave like sound not travel through?

a. solid
   b. liquid
   c. gas
   d. vacuum

3. A longitudinal wave has a compression to compression distance of 10 m. It takes the wave 5 s to pass a point.
   a. What is the wavelength of the longitudinal wave?
   b. What is the speed of the wave?
4. A flute produces a musical sound travelling at a speed of $320\,\text{m}\cdot\text{s}^{-1}$. The frequency of the note is 256 Hz. Calculate:
   a. the period of the note
   b. the wavelength of the note

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(1.) 003p (2.) 003q (3.) 003r (4.) 003s

Sound 10

Introduction

Have you ever thought about how amazing your sense of hearing is? It is actually pretty remarkable that we can hear the huge range of sounds and determine direction so quickly. How does something actually make a sound that you can hear? Anything that generates a disturbance in the air creates a pulse that travels away from the place where is was created. If this pulse enters your ear it can cause your ear drum to vibrate which is how you hear. If the source of the pulse creates a train of pulses then the disturbance is a wave. See introductory video: (Video: VPdxu at www.everythingscience.co.za)

We generally say that sound is a wave. Sound waves are longitudinal, pressure waves, that means that the waves consists of compressions and rarefactions of the pressure of the air.

Sound waves

A tuning fork is an instrument used by musicians to create sound waves of a specific frequency. They are often used to tune musical instruments.

Sound waves coming from a tuning fork are caused by the vibrations of the tuning fork which push against the air particles in front of it. As the air particles are pushed together a compression is formed. The particles behind the compression move further apart causing a rarefaction. As the particles continue to push against each other, the sound wave travels through the air. Due to this motion of the particles, there is a constant variation in the pressure in the air. Sound waves are therefore pressure waves. This means that in media where the particles are closer together, sound waves will travel faster.

Tuning fork

Photo by amonya on Flickr.com

See video: VPdya at www.everythingscience.co.za

Sound waves travel faster through liquids, like water, than through the air because water is denser than air (the particles are closer together). Sound waves travel faster in solids than in liquids.

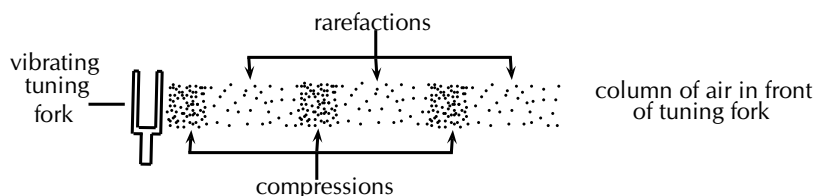



Figure 10.2: Sound waves are pressure waves and need a medium through which to travel.

> **Tip**
>
> A sound wave is a pressure wave. This means that regions of high pressure (compressions) and low pressure (rarefactions) are created as the sound source vibrates. These compressions and rarefactions arise because the source vibrates longitudinally and the longitudinal motion of air produces pressure fluctuations.

Activity: *Build your own telephone*

Have you ever wondered if you can actually use tin cans or cups to make a telephone? Try it and see!
What you need:

- Two tin cans or paper paper cups
- String
- Toothpicks or small sticks

Try This:

1. Tie a toothpick on each end of a length of string.
2. Make a hole in the base of the can or cup. Poke the toothpick through the end of the can. Pull the string tight so the toothpick rests on the inside bottom of the can. Put one can at each end of the string. (You may want to experiment with different cans or cups and strings or wires to see what works best.)
3. Hold the string tight and talk into one of the cans. The person at the other end should be able to hear you. Why does the string have to be tight?
4. Try to make a party line by tying a third string and can or cup onto the middle of the string. Can everybody talk to everybody else?

Sound waves need something to travel through. Usually they travel through air, but they can travel much faster and farther through a string. The string has to be tight or else the sound wave cannot travel through it. The cup helps to amplify the sound on the other end.

Speed of sound

ESACZ

The speed of sound depends on the medium the sound is travelling in. Sound travels faster in solids than in liquids, and faster in liquids than in gases. This is because the density of solids is higher than that of liquids which means that the particles are closer together. Sound can be transmitted more easily.

FACT

The speed of sound in air, at sea level, at a temperature of 21°C and under normal atmospheric conditions, is $344\,\text{m}\cdot\text{s}^{-1}$.

See video: VPeac at www.everythingscience.co.za

The speed of sound also depends on the temperature of the medium. The hotter the medium is, the faster its particles move and therefore the quicker the sound will travel through the medium. When we heat a substance, the particles in that substance have more kinetic energy and vibrate or move faster. Sound can therefore be transmitted more easily and quickly in hotter substances.

Sound waves are pressure waves. The speed of sound will therefore be influenced by the pressure of the medium through which it is travelling. At sea level the air pressure is higher than high up on a mountain. Sound will travel faster at sea level where the air pressure is higher than it would at places high above sea level.

Substance	v ($\text{m}\cdot\text{s}^{-1}$)
aluminium	6420
brick	3650
copper	4760
glass	5100
gold	3240
lead	2160
water, sea	1531
air, 0 °C	331
air, 20 °C	343

Table 10.1: The speed of sound in different materials.

Informal experiment: *Measuring the speed of sound in air*

Aim: To measure the speed of sound.

Apparatus:

- Starter's gun or anything that can produce a loud sound in response to visible action

- Stopwatch

Method: The speed of sound can be measured because light travels much faster than sound. Light travels at about 300 000 m · s^{-1} (you will learn more about the speed of light in the next chapter) while sound only travels at about 300 m · s^{-1}. This difference means that over a distance of 300 m, the light from an event will reach your eyes almost instantly but there will be an approximate half a second lag before you hear the sound produced. Thus if a starter's pistol is fired from a great distance, you will see the smoke immediately but there will be a lag before you hear the sound. If you know the distance and the time then you can calculate the speed (distance divided by time). You don't need a gun but anything that you can see producing a loud sound.

Try this:

1. Find a place where you know the precise, straight-line distance between two points (maybe an athletics track)
2. Someone needs to stand at the one point to produce the sound
3. Another person needs to stand at the other point with the stop watches
4. The person with the stopwatch should start the stopwatch when they see the other person make the sound and stop the stopwatch when they hear the sound (do this a few times and write the times down)

Results:

Time (s)	Distance (m)	v (m · s^{-1})
Averages		

You can now calculate the speed to sound by dividing the distance by the time. Remember to work in S.I. units (metres and seconds). If you took multiple readings then you can sum them and divide by the number of readings to get an average time reading. Use the average time to calculate the speed:

$$v = \frac{D}{t}$$

Conclusions: Some questions to ask:

- What is your reaction time on the stopwatch? You can test this by starting it and then trying to stop it immediately.
- What was the forecast temperature on the day of the measurement?
- Was it humid or very dry?

Discuss what might change the speed of sound that you measured.

You can vary this experiment by trying it on days when the weather is different as this can change air pressure and temperature.

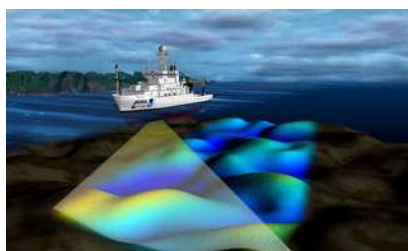
Reflection and echoes

When the sound waves collide with an object they are reflected. You can think of the individual particles that are oscillating about their equilibrium position colliding into the object when the wave passes. They bounce off the object causing the wave to be reflected.

In a space with many small objects there are reflections at every surface but they are too small and too mixed up to have an outcome that a human can hear. However, when there is an open space that has only large surfaces, for example a school hall that is empty, then the reflected sound can actually be heard. The sound wave is reflected in such a wave that the wave looks the same but is moving in the opposite direction. See video: VPebb at www.everythingscience.co.za

This means that if you stand in a hall and loudly say “hello” you will hear yourself say “hello” a split second later. This is an echo. This can also happen outdoors in a wide open space with a large reflecting surface nearby, like standing near a mountain cliff in an area with no trees or bushes.

This is a very useful property of waves.

SONAR

Ships on the ocean make use of the reflecting properties of sound waves to determine the depth of the ocean. A sound wave is transmitted and bounces off the seabed. Because the speed of sound is known and the time lapse between sending and receiving the sound can be measured, the distance from the ship to the bottom of the ocean can be determined, This is called sonar, which is an acronym for **So**und **N**avigation **A**nd **R**anging.

Example 1: SONAR

QUESTION

A ship sends a signal to the bottom of the ocean to determine the depth of the ocean. The speed of sound in sea water is 1450 m · s^{-1} If the signal is received 1,5 seconds later, how deep is the ocean at that point?

SOLUTION

Step 1 : ***Identify what is given and what is being asked:***

$$\begin{aligned} s &= 1450 \text{ m.s}^{-1} \\ t &= 1,5 \text{ s there and back} \\ \therefore t &= 0,75 \text{ s one way} \\ d &= ? \end{aligned}$$

Step 2 : ***Calculate the distance:***

$$\begin{aligned} \text{Distance} &= \text{speed} \times \text{time} \\ D &= s \times t \\ &= 1450 \text{ m} \cdot \text{s}^{-1} \times 0,75s \\ &= 1087,5 \text{ m} \end{aligned}$$

Echolocation

Animals like dolphins and bats make use of sounds waves to find their way. Just like ships on the ocean, bats use sonar to navigate. Waves that are sent out are reflected off the objects around the animal. Bats, or dolphins, then use the reflected sounds to form a “picture” of their surroundings. This is called echolocation.

Characteristics of a sound wave

Since sound is a wave, we can relate the properties of sound to the properties of a wave. The basic properties of sound are: pitch, loudness and tone.

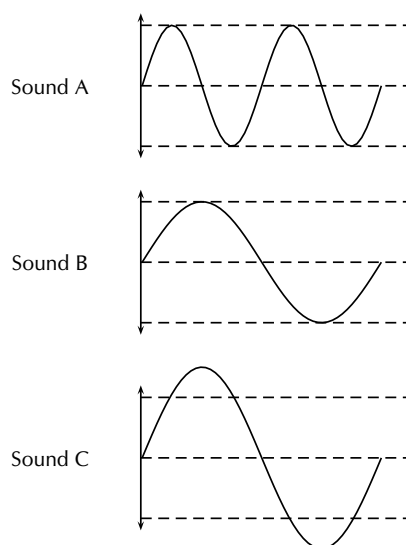



Figure 10.3: Pitch and loudness of sound. Sound B has a *lower* pitch (lower frequency) than Sound A and is *softer* (smaller amplitude) than Sound C.

Pitch

The frequency of a sound wave is what your ear understands as pitch. A higher frequency sound has a higher pitch, and a lower frequency sound has a lower pitch. In Figure 10.3 sound A has a higher pitch than sound B. For instance, the chirp of a bird would have a high pitch, but the roar of a lion would have a low pitch.

The human ear can detect a wide range of frequencies. Frequencies from 20 to 20 000 Hz are audible to the human ear. Any sound with a frequency below 20 Hz is known as an **infrasound** and any sound with a frequency above 20 000 Hz is known as an **ultrasound**.

Table 10.2 lists the ranges of some common animals compared to humans.

Table 10.2: Range of frequencies

	lower frequency (Hz)	upper frequency (Hz)
Humans	20	20 000
Dogs	50	45 000
Cats	45	85 000
Bats	20	120 000
Dolphins	0,25	200 000
Elephants	5	10 000

Activity: *Range of wavelengths*

Using the information given in Table 10.2, calculate the lower and upper wavelengths that each species can hear. Assume the speed of sound in air is $344\ \text{m} \cdot \text{s}^{-1}$.

Loudness

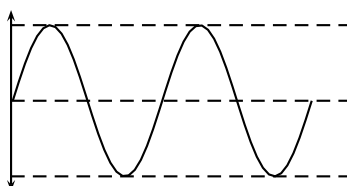
The amplitude of a sound wave determines its loudness or volume. A larger amplitude means a louder sound, and a smaller amplitude means a softer sound. In Figure 10.3 sound C is louder than sound B. The vibration of a source sets the amplitude of a wave. It transmits energy into the medium through its vibration. More energetic vibration corresponds to larger amplitude. The molecules move back and forth more vigorously.

The loudness of a sound is also determined by the sensitivity of the ear. The human ear is more sensitive to some frequencies than to others. The volume we receive thus depends on both the amplitude of a sound wave and whether its frequency lies in a region where the ear is more or less sensitive.

Exercise 10 - 1

Study the following diagram representing a musical note. Redraw the diagram for a note

1. with a higher pitch
2. that is louder

3. that is softer

More practice video solutions or help at www.everythingscience.co.za

(1.) 003t

Activity:	*Comparing sound generating instruments*

The size and shape of instruments influences the sounds that they are able to produce. Find some instruments that have different physical characteristics and compare their sounds. You could:

Option 1: Vuvuzelas:
Compare the sounds made by blowing through vuvuzelas of different sizes. You will need to find a few different vuvuzelas. Take turns blowing the different ones, one at a time and record which you think is louder (amplitude), which is of higher pitch (frequency).

Option 2: Tuning forks:
Compare the sounds created by tapping tuning forks of different sizes. You will need to find a few different tuning forks. Take turns tapping the different ones, one at a time and record which you think is louder (amplitude), which is of higher pitch (frequency).

Option 3: Signal generator and oscilloscope:
Use a function generator connected to a speaker to produce sounds of different frequencies and amplitudes and use a microphone connected to an oscilloscope to display the characteristics of the different sounds produced.

Function generator
The function generator allows you to control the loudness and frequency of the sound being produced by the speaker. It will have controls for amplitude and frequency.

A function generator

Photograph by Audin on Flickr.com

Oscilloscope

The microphone can then pick up the sound and convert it to an electrical signal which can be displayed on the oscilloscope.

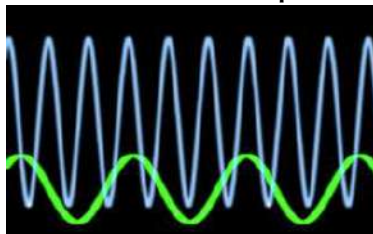
The most common oscilloscope controls are for amplitude, frequency, triggering, and channels. Once your teacher has helped you acquire a signal using the correct channel and triggering you will use the amplitude and frequency controls to display the characteristics of the sound being produced.

The amplitude adjustment of an oscilloscope controls how tall a given voltage will appear on the screen. The purpose of this adjustment is that you can see a very large or a very small signal on the same screen.

The frequency (or time) adjustment of an oscilloscope is how much time will a certain distance across the screen represent. The purpose of this adjustment is to be able to see a very quickly changing or a slowly changing signal on the same screen.

An oscilloscope

Photograph by Audin on Flickr.com

Two different oscilloscope traces

Photograph by Audin on Flickr.com

Note: *The display of the oscilloscope will show you a transverse wave pattern. This does not mean that sound waves are transverse waves but just shows that the pressure being measured is fluctuating because of a pressure wave.*

You will be able to experiment with different amplitudes and frequencies using the function generator and see what impact the changes have on the waveform picked up by the microphone.

See video: VPebn at www.everythingscience.co.za

Intensity of sound [NOT IN CAPS]

ESADE

Intensity is one indicator of amplitude. Intensity is the energy transmitted over a unit of area each second.

The unit of intensity is the **decibel** (symbol: dB).

Source	**Intensity** (dB)	**Times greater than hearing threshold**
Rocket Launch	180	10^{18}
Jet Plane	140	10^{14}
Threshold of Pain	120	10^{12}
Rock Band	110	10^{11}
Factory	80	10^{8}
City Traffic	70	10^{7}
Normal Conversation	60	10^{6}
Library	40	10^{4}
Whisper	20	10^{2}
Threshold of hearing	0	0

Table 10.3: Examples of sound intensities.

Vuvuzelas feature prominently at soccer events in South Africa. The intensity of the sound from a vuvuzela depends on how close you are. In Table 10.3 you can see how the intensity differs.

Vuvuzelas in action

Photo by Dundas Football Club on Flickr.com

Frequency (Hz)	At ear	Bell opening	1 m	2 m
125	36	62	38	35
250	92	106	82	85
500	103	121	102	101
1 000	106	122	108	100
2 000	101	122	110	101
4 000	97	109	110	102
5 000	93	111	109	100
8 000	87	110	107	98

Table 10.4: Average vuvuzela intensity measurements across frequencies at 4 distinct distances from the bell end of the vuvuzela (dBA) taken from South African Medical Journal (Cape Town, South Africa) **100** (4): 192

Ultrasound

Ultrasound is sound with a frequency that is higher than 20 kHz. Some animals, such as dogs, dolphins, and bats, have an upper limit that is greater than that of the human ear and can hear ultrasound.

Application	Lowest Frequency (kHz)	Highest Frequency (kHz)
Cleaning (e.g. jewellery)	20	40
Material testing for flaws	50	500
Welding of plastics	15	40
Tumour ablation	250	2000

Table 10.5: Different uses of ultrasound and the frequencies applicable.

The most common use of ultrasound is to create images, and has industrial and medical applications. The use of ultrasound to create images is based on the reflection and transmission of a wave at a boundary (when the wave goes from one substance to another). When an ultrasound wave travels inside an object that is made up of different materials such as the human body, each time it encounters a boundary, e.g. between bone and muscle, or muscle and fat, part of the wave is reflected and part of it is transmitted. The reflected rays are detected and used to construct an image of the object.

Ultrasound in medicine can visualise muscle and soft tissue, making them useful for scanning the organs, and is commonly used during pregnancy. Ultrasound is a safe, non-invasive method of looking inside the human body.

Ultrasound image of a unborn baby

Picture by mbaylor on Flickr.com

FACT

Ultrasound generator-/speaker systems are sold with claims that they frighten away rodents and insects, but there is no scientific evidence that the devices work; controlled tests have shown that rodents quickly learn that the speakers are harmless.

Ultrasound sources may be used to generate local heating in biological tissue, with applications in physical therapy and cancer treatment. Focused ultrasound sources may be used to break up kidney stones.

Ultrasonic cleaners, sometimes called supersonic cleaners, are used at frequencies from 20-40 kHz for jewellery, lenses and other optical parts, watches, dental instruments, surgical instruments and industrial parts. These cleaners consist of containers with a fluid in which the object to be cleaned is placed. Ultrasonic waves are then sent into the fluid. The main mechanism for cleaning action in an ultrasonic cleaner is actually the energy released from the collapse of millions of microscopic bubbles occurring in the liquid of the cleaner.

The physics of hearing [NOT IN CAPS]

ESADG

The human ear is divided into three main sections: the outer, middle, and inner ear. Let's follow the journey of a sound wave from the pinna (outermost part) to the auditory nerve (innermost part) which transmits a signal to the brain. The pinna is the part of the ear we typically think of when we refer to the ear. Its main function is to collect and focus a sound wave. The wave then travels through the ear canal until it meets the eardrum. The pressure fluctuations of the sound wave make the eardrum vibrate. The three very small bones of the middle ear, the malleus (hammer), the incus (anvil), and the stapes (stirrup), transmit the

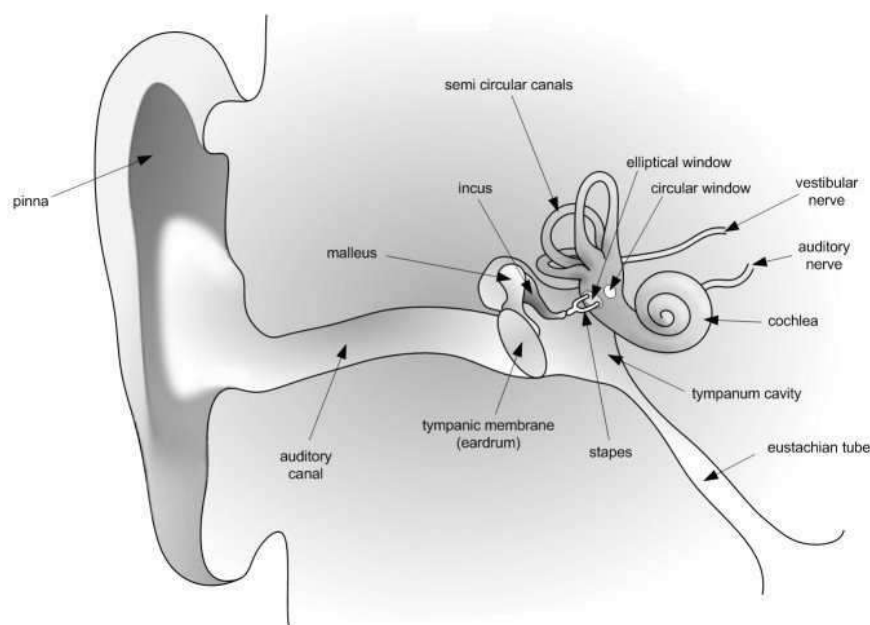



Figure 10.4: Diagram of the human ear.

signal through to the elliptical window. The elliptical window is the beginning of the inner ear. From the elliptical window the sound waves are transmitted through the liquid in the inner ear and interpreted as sounds by the brain. The inner ear, made of the semicircular canals, the cochlea, and the auditory nerve, is filled with fluid. The fluid allows the body to detect quick movements and maintain balance.

There are sounds which exceed the threshold of pain. Exposure to these sounds can cause immediate damage to hearing. In fact, exposure to sounds from 80 dB and above can damage hearing over time. Measures can be taken to avoid damage, such as wearing earplugs or ear muffs. Limiting exposure time and increasing distance between you and the source are also important steps for protecting your hearing.

Group Discussion: Importance of Safety Equipment

Working in groups of 5, discuss the importance of safety equipment such as ear protectors for workers in loud environments, e.g. those who use jack hammers or direct aeroplanes to their parking bays. Write up your conclusions in a one page report. Some prior research into the importance of safety equipment might be necessary to complete this group discussion.

Chapter 10 | Summary

See the summary presentation (▶ Presentation: VPecu at www.everythingscience.co.za)

- Sound waves are longitudinal waves
- The **frequency** of a sound is an indication of how high or low the *pitch* of the sound is.
- The human ear can hear frequencies from 20 to 20 000 Hz. **Infrasound** waves have frequencies lower than 20 Hz. **Ultrasound** waves have frequencies higher than 20 000 Hz.
- The **amplitude** of a sound determines its *loudness* or volume.
- The **tone** is a measure of the *quality* of a sound wave.
- The speed of sound in air is around $340\,\text{m}\cdot\text{s}^{-1}$. It is dependent on the temperature, height above sea level and the phase of the medium through which it is travelling.
- Sound travels faster when the medium is hot.
- Sound travels faster in a solid than a liquid and faster in a liquid than in a gas.
- Sound travels faster at sea level where the air pressure is higher.
- The intensity of a sound is the energy transmitted over a certain area. Intensity is a measure of frequency.
- Ultrasound can be used to form pictures of things we cannot see, like unborn babies or tumours.
- Echolocation is used by animals such as dolphins and bats to "see" their surroundings by using ultrasound.
- Ships use sonar to determine how deep the ocean is or to locate shoals of fish.

Physical Quantities		
Quantity	**Unit name**	**Unit symbol**
Velocity (v)	metre per second	$\text{m}\cdot\text{s}^{-1}$
Wavelength (λ)	metre	m
Amplitude (A)	metre	m
Period (T)	second	s
Frequency (f)	hertz	Hz (s^{-1})

Table 10.6: Units used in **sound**

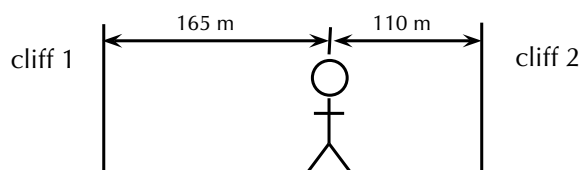
Chapter 10 End of chapter exercises

1. Choose a word from column B that best describes the concept in column A.

Column A	Column B
1. pitch of sound	A. amplitude
2. loudness of sound	B. frequency
3. quality of sound	C. speed
	D. waveform

2. A tuning fork, a violin string and a loudspeaker are producing sounds. This is because they are all in a state of:
   a. compression
   b. rarefaction
   c. rotation
   d. tension
   e. vibration
3. What would a drummer do to make the sound of a drum give a note of lower pitch?
   a. hit the drum harder
   b. hit the drum less hard
   c. hit the drum near the edge
   d. loosen the drum skin
   e. tighten the drum skin
4. What is the approximate range of audible frequencies for a healthy human?
   a. 0.2 Hz $\rightarrow$ 200 Hz
   b. 2 Hz $\rightarrow$ 2 000 Hz
   c. 20 Hz $\rightarrow$ 20 000 Hz
   d. 200 Hz $\rightarrow$ 200 000 Hz
   e. 2 000 Hz $\rightarrow$ 2 000 000 Hz
5. X and Y are different wave motions. In air, X travels much faster than Y but has a much shorter wavelength. Which types of wave motion could X and Y be?

	X	Y
1.	microwaves	red light
2.	radio	infra red
3.	red light	sound
4.	sound	ultraviolet
5.	ultraviolet	radio

6. Astronauts are in a spaceship orbiting the moon. They see an explosion on the surface of the moon. Why can they not hear the explosion?
   a. explosions do not occur in space
   b. sound cannot travel through a vacuum
   c. sound is reflected away from the spaceship
   d. sound travels too quickly in space to affect the ear drum
   e. the spaceship would be moving at a supersonic speed
7. A man stands between two cliffs as shown in the diagram and claps his hands once.

   Assuming that the velocity of sound is $330\,\text{m}\cdot\text{s}^{-1}$, what will be the time interval between the two loudest echoes?
   a. $\frac{2}{3}$ s
   b. $\frac{1}{6}$ s
   c. $\frac{5}{6}$ s
   d. 1 s
   e. $\frac{1}{3}$ s
8. A dolphin emits an ultrasonic wave with frequency of 0,15 MHz. The speed of the ultrasonic wave in water is $1500\,\text{m}\cdot\text{s}^{-1}$. What is the wavelength of this wave in water?
   a. 0,1 mm
   b. 1 cm
   c. 10 cm
   d. 10 m
   e. 100 m
9. The amplitude and frequency of a sound wave are both increased. How are the loudness and pitch of the sound affected?

	loudness	pitch
A	increased	raised
B	increased	unchanged
C	increased	lowered
D	decreased	raised
E	decreased	lowered

10. A jet fighter travels slower than the speed of sound. Its speed is said to be:

- **a**. Mach 1
- **b**. supersonic
- **c**. subsonic
- **d**. hypersonic
- **e**. infrasonic

11. A sound wave is different from a light wave in that a sound wave is:

- **a**. produced by a vibrating object and a light wave is not.
- **b**. not capable of travelling through a vacuum.
- **c**. not capable of diffracting and a light wave is.
- **d**. capable of existing with a variety of frequencies and a light wave has a single frequency.

12. At the same temperature, sound waves have the fastest speed in:

- **a**. rock
- **b**. milk
- **c**. oxygen
- **d**. sand

13. Two sound waves are travelling through a container of nitrogen gas. The first wave has a wavelength of 1,5 m, while the second wave has a wavelength of 4,5 m. The velocity of the second wave must be:

- **a**. $\frac{1}{9}$ the velocity of the first wave.
- **b**. $\frac{1}{3}$ the velocity of the first wave.
- **c**. the same as the velocity of the first wave.
- **d**. three times larger than the velocity of the first wave.
- **e**. nine times larger than the velocity of the first wave.

14. A lightning storm creates both lightning and thunder. You see the lightning almost immediately since light travels at 3×10^8 m · s^{-1}. After seeing the lightning, you count 5 s and then you hear the thunder. Calculate the distance to the location of the storm.

15. A person is yelling from a second story window to another person standing at the garden gate, 50 m away. If the speed of sound is 344 m·s^{-1},

how long does it take the sound to reach the person standing at the gate?

16. Person 1 speaks to person 2. Explain how the sound is created by person 1 and how it is possible for person 2 to hear the conversation.

17. Sound cannot travel in space. Discuss what other modes of communication astronauts can use when they are outside the space shuttle?

18. An automatic focus camera uses an ultrasonic sound wave to focus on objects. The camera sends out sound waves which are reflected off distant objects and return to the camera. A sensor detects the time it takes for the waves to return and then determines the distance an object is from the camera. If a sound wave (speed = 344 m·s^{-1}) returns to the camera 0,150 s after leaving the camera, how far away is the object?

19. Calculate the frequency (in Hz) and wavelength of the annoying sound made by a mosquito when it beats its wings at the average rate of 600 wing beats per second. Assume the speed of the sound waves is 344 m·s^{-1}.

20. How does halving the frequency of a wave source affect the speed of the waves?

21. Humans can detect frequencies as high as 20 000 Hz. Assuming the speed of sound in air is 344 m·s^{-1}, calculate the wavelength of the sound corresponding to the upper range of audible hearing.

22. An elephant trumpets at 10 Hz. Assuming the speed of sound in air is 344 m·s^{-1}, calculate the wavelength of this infrasonic sound wave made by the elephant.

23. A ship sends a signal out to determine the depth of the ocean. The signal returns 2,5 seconds later. If sound travels at 1450 m.s^{-1} in sea water, how deep is the ocean at that point?

24. A person shouts at a cliff and hears an echo from the cliff 1 s later. If the speed of sound is $344\,\mathrm{m \cdot s^{-1}}$, how far away is the cliff?

25. Select a word from Column B that best fits the description in Column A:

Column A	**Column B**
1. waves in the air caused by vibrations	**A.** longitudinal waves
2. waves that move in one direction, but medium moves in another	**B.** frequency
3. waves and medium that move in the same direction	**C.** period
4. the distance between consecutive points of a wave which are in phase	**D.** amplitude
5. how often a single wavelength goes by	**E.** sound waves
6. half the difference between high points and low points of waves	**F.** standing waves
7. the distance a wave covers per time interval	**G.** transverse waves
8. the time taken for one wavelength to pass a point	**H.** wavelength
	I. music
	J. sounds
	K. wave speed

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(1.) 003u (2.) 003v (3.) 003w (4.) 003x (5.) 003y (6.) 003z
(7.) 0040 (8.) 0041 (9.) 0042 (10.) 0043 (11.) 0044 (12.) 0045
(13.) 0046 (14.) 0048 (15.) 0049 (16.) 004c (17.) 004d (18.) 004e
(19.) 004f (20.) 004g (21.) 004h (22.) 004i (23.) 004j (24.) 004k
(25.) 004m

Electromagnetic radiation 11

What is electromagnetic radiation?

The most common example of electromagnetic (EM) radiation is visible light. Everyone is very familiar with light in everyday life, you can only see things because light bounces off them and enters your eyes. This alone makes it worthwhile to learn about it but there are also very many other applications of EM radiation. It is called electromagnetic because there are electric and magnetic fields making up the radiation. We will look at this in more detail a little later. See introductory video: (Video: VPefg at www.everythingscience.co.za)

In everyday experience, light doesn't seem to have many special properties but it does:

- **A huge spectrum**: The light we can see (visible EM radiation) is only a small part of all of the EM radiation (electromagnetic spectrum) that exists.
- **Nature's speed limit**: Nothing moves faster than the speed of light.
- **Wave nature**: All EM radiation has the ability to behave like a wave which we call wave-like behaviour.
- **Particle nature**: All EM radiation has the ability to behave like a particle which we call particle-like behaviour.
- **No medium required**: EM radiation can propagate without a medium through which to move even though they are waves.

Two important things to notice, we have mentioned:

1. waves without a medium and
2. being both a particle and a wave.

We will discuss this in the following sections and in even more detail in Grades 11 and 12.

Wave-like nature of EM radiation

 ESADI

If you watch a colony of ants walking up the wall, they look like a thin continuous black line. But as you look closer, you see that the line is made up of thousands of separated black ants.

Light and all other types of electromagnetic radiation seem like a continuous wave at first, but when one performs experiments with light, one can notice that light can have both wave- and particle-like properties. Just like the individual ants, light can also be made up of individual bundles of energy, or quanta of light.

Light has both wave-like and particle-like properties (wave–particle duality), but only shows one or the other, depending on the kind of experiment we perform. A wave-type experiment shows the wave nature, and a particle-type experiment shows particle nature. One **cannot** test the wave and the particle nature at the same time. A particle of light is called a photon.

DEFINITION: Photon

A photon is a quantum (energy packet) of light.

Fields

ESADJ

Accelerating charges emit electromagnetic waves. A changing electric field generates a magnetic field and a changing magnetic field generates an electric field. This is the principle behind the propagation of electromagnetic waves, because electromagnetic waves, unlike sound waves, do not need a medium to travel through. See video: VPeka at www.everythingscience.co.za

EM waves propagate when an electric field oscillating in one plane produces a magnetic field oscillating in a plane at right angles to it, which produces an oscillating electric field, and so on. The propagation of electromagnetic waves can be described as *mutual induction*. The changing electric field is responsible for inducing the magnetic field and vice versa.

We use E to denote electric fields and B to denote magnetic fields.

These concepts will be covered in more detail in Grade 11.

These mutually regenerating fields, most commonly described as self-propagating, travel through empty space at a constant speed of approximately $3 \times 10^8\,\text{m} \cdot \text{s}^{-1}$, represented by c. We will use $3 \times 10^8\,\text{m} \cdot \text{s}^{-1}$ for all of our calculations in this book. Although an electromagnetic wave can travel through empty space, it can also travel through a medium (such as water and air). When an electromagnetic wave travels through a medium, it travels slower than it would through empty space (vacuum).
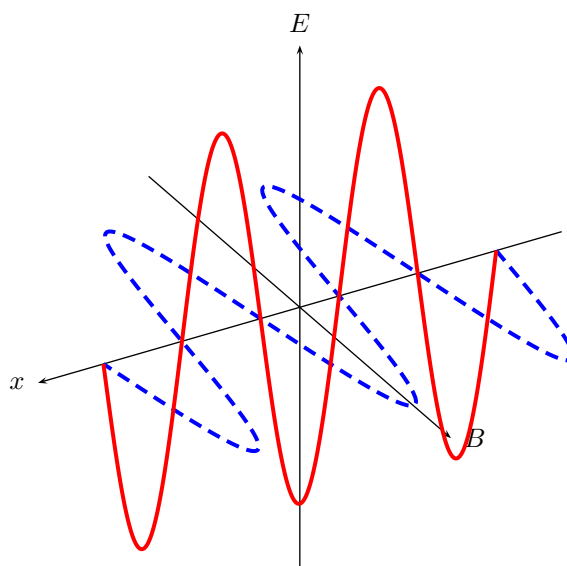
Figure 11.2: A diagram showing the mutually regenerating electric field (red (solid) line) and magnetic field (blue (dashed) line).

Since an EM radiation is a wave, the following equation still applies:

$$v = f \cdot \lambda$$

Except that we can replace v with c:

$$\boxed{c = f \cdot \lambda}$$

Example 1: EM radiation I

QUESTION

Calculate the frequency of an electromagnetic wave with a wavelength of $4,2 \times 10^{-7}$ m.

SOLUTION

Step 1 : **Wave equation**

We use the formula: $c = f\lambda$ to calculate frequency. The speed of light is a constant 3×10^8 m · s^{-1}.

Step 2 : **Calculate**

$$\begin{aligned} c &= f\lambda \\ 3 \times 10^8 \text{ m} \cdot \text{s}^{-1} &= f \times 4,2 \times 10^{-7} \text{ m} \\ f &= 7,14 \times 10^{14}\text{Hz} \end{aligned}$$

Step 3 : **Quote the final answer**

The frequency is $7,14 \times 10^{14}$Hz.

Example 2: EM Radiation II

QUESTION

An electromagnetic wave has a wavelength of 200 nm. What is the frequency of the radiation?

SOLUTION

Step 1 : **What do we know?**

Recall that all radiation travels at the speed of light (c) in vacuum. Since the question does not specify through what type of material the wave is

travelling, one can assume that it is travelling through a vacuum. We can identify two properties of the radiation - $wavelength$ (200 nm) and speed (c).

Step 2 : ***Apply the wave equation***

$$\begin{aligned} c &= f\lambda \\ 3 \times 10^{8} \text{ m} \cdot \text{s}^{-1} &= f \times 200 \times 10^{-9} \text{ m} \\ f &= 1.5 \times 10^{15} \text{ Hz} \end{aligned}$$

Step 3 : ***Quote the final answer***

The frequency is 1.5×10^{15} Hz.

Electromagnetic spectrum

ESADK

EM radiation is classified into types according to the frequency of the wave: these types include, in order of increasing frequency, radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays.

See video: VPemp at www.everythingscience.co.za

Table 11.3 lists the wavelength and frequency ranges of the divisions of the electromagnetic spectrum.

Category	Range of Wavelengths (nm)	Range of Frequencies (Hz)
gamma rays	< 1	$> 3 \times 10^{19}$
X-rays	1-10	3×10^{17}-3×10^{19}
ultraviolet light	10-400	$7,5 \times 10^{14}$-3×10^{17}
visible light	400-700	$4,3 \times 10^{14}$-$7,5 \times 10^{14}$
infrared	700-10^5	3×10^{12}-$4,3 \times 10^{19}$
microwave	$10^5 - 10^8$	3×10^{9}-3×10^{12}
radio waves	$> 10^8$	$< 3 \times 10^{9}$

Table 11.1: Electromagnetic spectrum

Examples of some uses of electromagnetic waves are shown in Table 11.3.

Category	Uses
gamma rays	used to kill the bacteria in marshmallows and to sterilise medical equipment
X-rays	used to image bone structures
ultraviolet light	bees can see into the ultraviolet because flowers stand out more clearly at this frequency
visible light	used by humans to observe the world
infrared	night vision, heat sensors, laser metal cutting
microwave	microwave ovens, radar
radio waves	radio, television broadcasts

Table 11.2: Uses of EM waves

Exercise 11 - 1

1. Arrange the following types of EM radiation in order of increasing frequency: infrared, X-rays, ultraviolet, visible, gamma.

2. Calculate the frequency of an EM wave with a wavelength of 400 nm.

3. Give an example of the use of each type of EM radiation, i.e. gamma rays, X-rays, ultraviolet light, visible light, infrared, microwave and radio and TV waves.

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(1.) 004q (2.) 004r (3.) 004s
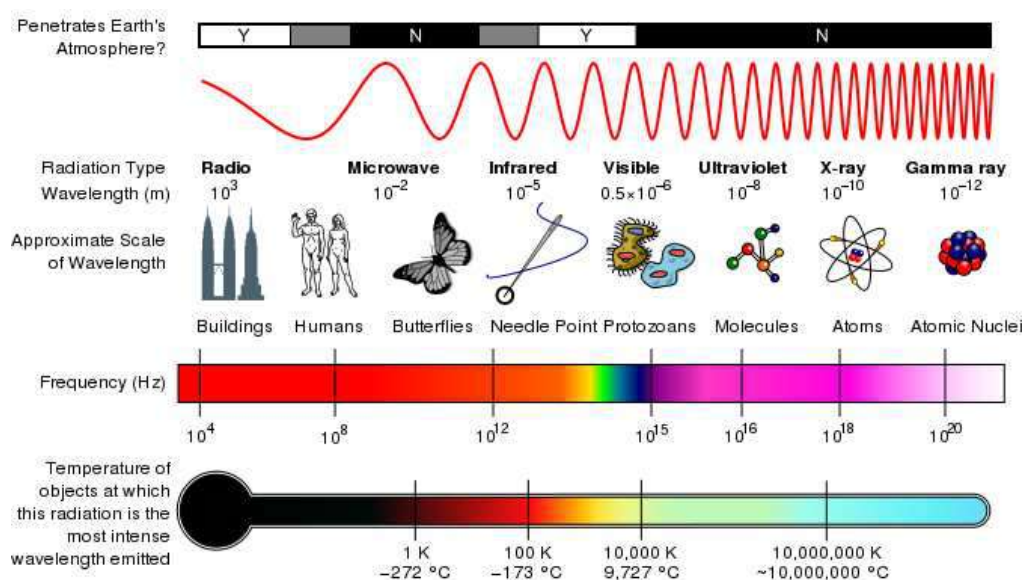
Figure 11.3: The electromagnetic spectrum as a function of frequency. The different types according to wavelength are shown as well as everyday comparisons.

EM radiation in the visible part of the spectrum is scattered off all of the objects around us. This EM radiation provides the information to our eyes that allows us to see. The frequencies of radiation the human eye is sensitive to constitute only a very small part of all possible frequencies of EM radiation. The full set of EM radiation is called the electromagnetic spectrum. To simplify things the EM spectrum divided into sections (such as radio, microwave, infrared, visible, ultraviolet, X-rays and gamma-rays). See video: VPfdy at www.everythingscience.co.za

The EM spectrum is continuous (has no gaps) and infinite. Due to technological limitations,

we can only use electromagnetic radiation with wavelengths between 10^{-14}m and 10^{15}m.

Penetrating ability of EM radiation

ESADL

Different frequencies of EM radiation have different degrees of penetration. For example, if we take the human body as the object, visible light is reflected off the surface of the human body, ultra-violet light (from sunlight) damages the skin, but X-rays are able to penetrate the skin and bone and allow for pictures of the inside of the human body to be taken.

If we compare the energy of visible light to the energy of X-rays, we find that X-rays have a much higher frequency. Usually, electromagnetic radiation with higher frequency (energy) have a higher degree of penetration than those with low frequency.

Certain kinds of electromagnetic radiation such as ultra-violet radiation, X-rays and gamma rays are very dangerous. Radiation such as these are called ionising radiation. Ionising radiation transfers energy as it passes through matter, breaking molecular bonds and creating ions.

Excessive exposure to radiation, including sunlight, X-rays and all nuclear radiation, can cause destruction of biological tissue. Luckily, the Earth's atmosphere protects us and other living beings on Earth from most of the harmful EM radiation.

Ultraviolet (UV) radiation and the skin

UVA and UVB are different ranges of frequencies for ultraviolet (UV) light. UVA and UVB can damage collagen fibres which results in the speeding up skin ageing. In general, UVA is the least harmful, but it can contribute to the ageing of skin, DNA damage and possibly skin cancer. It penetrates deeply and does not cause sunburn.

UVB light can cause skin cancer. The radiation excites DNA molecules in skin cells, resulting in possible cancerous mutations. In particular, the layer of ozone in the atmosphere protects us from UVB radiation. The connection between UVB radiation and cancer is one of the reasons for concern about the depletion of ozone in the atmosphere. See video: VPfeu at www.everythingscience.co.za

As a defence against UV radiation, the body tans when exposed to moderate (depending on skin type) levels of radiation by releasing the brown pigment melanin. This helps to block UV penetration and prevent damage to the vulnerable skin tissue deeper down. Sun-tan lotion, often referred to as sunblock or sunscreen, partly blocks UV radiation and is widely available. These products have a sun protection factor (SPF) rating (usually indicated on the container) that indicate how much protection the product provides against UVB radiation.

The SPF rating does not specify protection against UVA radiation. Some sunscreen lotion now includes compounds such as titanium dioxide which helps protect against UVA rays. Other UVA-blocking compounds found in sunscreen include zinc oxide and avobenzone.

What makes a good sunscreen?

- UVB protection: Padimate O, Homosalate, Octisalate (octyl salicylate), Octinoxate (octyl methoxycinnamate)
- UVA protection: Avobenzone
- UVA/UVB protection: Octocrylene, titanium dioxide, zinc oxide, Mexoryl (ecamsule)

Another means to block UV is by wearing sun protective clothing. This is clothing that has a UPF rating that describes the protection given against both UVA and UVB.

Ultraviolet radiation and the eyes

High intensity UVB light can cause damage to the eyes and exposure can cause welder's flash (photo keratitis or arc eye) and may lead to cataracts and other medical issues.

Protective eyewear is beneficial to those who are working with or those who might be exposed to ultraviolet radiation. Given that light may reach the eye from the sides, full coverage eye protection is best. Ordinary, untreated glasses give some protection. Most plastic lenses give more protection than glass lenses. Some plastic lens materials, such as polycarbonate, block most UV. Most contact lenses help to protect the retina by absorbing UV radiation.

X-rays

While X-rays are used significantly in medicine, prolonged exposure to X-rays can lead to cell damage and cancer.
For example, a mammogram is an X-ray of the human breast to detect breast cancer, but if a woman starts having regular mammograms when she is too young, her chances of getting breast cancer increases.

Gamma-rays

Due to their high energies, gamma-rays are able to cause serious damage when absorbed by living cells.

Gamma-rays are not stopped by the skin and can induce DNA alteration by interfering with the genetic material of the cell. DNA double-strand breaks are generally accepted to be the most biologically significant lesion by which ionising radiation causes cancer and hereditary disease.

A study done on Russian nuclear workers exposed to external whole-body gamma-radiation at high doses shows a link between radiation exposure and death from leukaemia, lung, liver, skeletal and other solid cancers.

Cellphones and microwave radiation

Cellphone radiation and health concerns have been raised, especially following the enormous increase in their use. This is because cellphones use electromagnetic waves in the microwave range. These concerns have induced a large body of research. Concerns about effects on health have also been raised regarding other digital wireless systems, such as data communication networks. In 2009 the World Health Organisation announced that they have found a link between brain cancer and cellphones. However, there is still no firm evidence for this and the link is tenuous at best. You can find out more at http://www.who.int/mediacentre/factsheets/fs193/en/[a]

[a] http://www.who.int/mediacentre/factsheets/fs193/en/

Cellphone users are recommended to minimise their exposure to the radiation, by for example:

1. Use hands-free to decrease the radiation to the head.
2. Keep the mobile phone away from the body.
3. Do not use a cellphone in a car without an external antenna.

Exercise 11 - 2

1. Indicate the penetrating ability of the different kinds of EM radiation and relate it to energy of the radiation.

2. Describe the dangers of gamma rays, X-rays and the damaging effect of ultra-violet radiation on skin.

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(1.) 004t (2.) 004u

Particle-like nature of EM radiation

ESADM

When we talk of electromagnetic radiation as a particle, we refer to photons, which are packets of energy. The energy of the photon is related to the wavelength of electromagnetic radiation according to:

DEFINITION: Planck's constant

Planck's constant is a physical constant named after Max Planck.
$h = 6,63 \times 10^{-34}$ J · s

The energy of a photon can be calculated using the formula:

$$\boxed{E = hf}$$

or

$$\boxed{E = h\frac{c}{\lambda}},$$

where E is the energy of the photon in joules (J), h is Planck's constant, c is the speed of light, f is the frequency in hertz (Hz) and λ is the wavelength in metres (m).

The higher the frequency of EM radiation, the higher the energy.

Example 3: *Calculating the energy of a photon I*

QUESTION

Calculate the energy of a photon with a frequency of 3×10^{18} *Hz*

SOLUTION

Step 1 : ***Analyse the question***

You are asked to determine the energy of a photon given the frequency. The frequency is in standard units and we know the relationship between frequency and energy.

Step 2 : ***Apply the equation for the energy of a photon***

$$\begin{aligned} E &= hf \\ &= 6,63 \times 10^{-34} \text{ J} \cdot \text{s} \times 3 \times 10^{18} \text{ Hz} \\ &= 2 \times 10^{-15} \text{ J} \end{aligned}$$

Step 3 : ***Quote the final result***

The energy is 2×10^{-15} J

Example 4: *Calculating the energy of a photon II*

QUESTION

What is the energy of an ultraviolet photon with a wavelength of 200 nm?

SOLUTION

Step 1 : ***Analyse the question***

You are asked to determine the energy of a photon given the wavelength. The wavelength is in standard units and we know the relationship between frequency and energy. We also know the relationship between wavelength and frequency, the equation for wave speed. The speed of light is a constant that we know.

Step 2 : ***Apply principles***

First we determine the frequency in terms of the wavelength.

$$c = f \cdot \lambda$$
$$f = \frac{c}{\lambda}$$

We can substitute this into the equation for the energy of a photon, $E = hf$, allowing us to deduce:

$$E = h\frac{c}{\lambda}$$

Step 3 : ***Do the calculation***

$$\begin{aligned} E &= h\tfrac{c}{\lambda} \\ &= \left(6,63 \times 10^{-34}\ \text{J} \cdot \text{s}\right) \tfrac{3 \times 10^{8} \text{m} \cdot \text{s}^{-1}}{200 \times 10^{-9}\ \text{m}} \\ &= 9,939 \times 10^{-10}\,\text{J} \end{aligned}$$

Step 4 : ***Quote the final result***

The energy of the photon is $9,939 \times 10^{-10}$ J

Exercise 11 - 3

1. How is the energy of a photon related to its frequency and wavelength?
2. Calculate the energy of a photon of EM radiation with a frequency of 10^{12} Hz.
3. Determine the energy of a photon of EM radiation with a wavelength of 600 nm.

More practice video solutions or help at www.everythingscience.co.za

(1.) 004v (2.) 004w (3.) 004x

Animal behaviour [IKS]

ESADN

People have believed that animals can predict earthquakes and other natural disasters for centuries. As early as 373 B.C., historians recorded a massive exodus of animals, including rats, snakes and weasels, from the Greek city of Helice days before a quake struck causing massive devastation.

This topic is much debated and different behaviours are sometimes seen for different kinds of animals, for example:

- **Dogs and cats**: are believed by pet owners to howl or bite their owners before natural disasters, they cite factors like a much stronger sense of smell.
- **Sharks**: researchers in Florida have reported that sharks are observed to move to deeper water before hurricanes, possibly because of a sensitivity to changes in the air pressure preceding the hurricane.
- **Rodents**: rodents that live underground will often flee their holes and burrows before a disaster. Scientists from the California Institute of Technology have noted that there are many changes preceding earthquakes such as tilting of the Earth. Rodents are often more sensitive to such small changes and will react to these changes.

- **Elephants**: will allegedly trumpet and flee to higher ground before a tsunami arrived. This is attributed to their being more sensitive to vibrations on the Earth's surface.

Many researchers argue that animals detect certain natural signals, such as the early tremblings of an earthquake, long before humans. This means that the animals have opportunity to react before we can. However it can be said that they exhibit no special understanding, they just flee as would any person hearing a shout of fire.

Another problem cited with these seemingly clairvoyant animals is that their psychic powers often are based on behaviours that people only recall after the event. Some animal behaviours happen frequently, but are not remembered unless an earthquake, tsunami, or mud slide follows. For example, if you see a dog cross a road, you just remember you saw a dog cross the road. But if an earthquake shook your neighbourhood five minutes later, would you say the dog was fleeing?

Activity:	*Animals and natural disasters*

Carry out research on the behaviour of animals before natural disasters.

Pick one type of natural disaster (earthquake, flood, tsunami, etc.) and see what you can find about animals reacting to that type of disaster. Ask people you know about what they have heard to get a sense of folklore.

Then research the topic to find more information and remember to critically assess all information. Things to consider:

- What scientific research has been conducted?
- Which countries does that type of disaster usually occur in?
- Do any of the native people of that country have legends/ideas about animals reacting to the disaster?
- What do people believe leads to this behaviour? i.e. do the animals have some mystic ability or are they more sensitive to anything then we are (such as low frequency radiation)

Some suggested resources for information are:

- *http://www.unep.org/ik/*
- *http://earthquake.usgs.gov/learn/topics/animal_eqs.php*
- *http://biology.about.com/od/animalbehavior/a/aa123104a.htm*
- *http://news.nationalgeographic.com/news/2003/11/1111_031111_earthquakeanimals_2.*
- *Bats sing, mice giggle* by Karen Shanor and Jagmeet Kanwal
- *http://www.sheldrake.org/homepage.html*
- *http://nationalzoo.si.edu/SCBI/AnimalCare/News/earthquake.cfm*
- *http://www.animalvoice.com/animalssixthsense.htm*

Present your findings to your class. Critically analyse all the information you collect and decide what you believe.

Chapter 11 | Summary

See the summary presentation (▶ Presentation: VPfhw at www.everythingscience.co.za)

- Electromagnetic radiation has both a wave and a particle nature.
- Electromagnetic waves travel at a speed of approximately $3 \times 10^8\ m \cdot s^{-1}$ in a vacuum.

- The Electromagnetic spectrum consists of the following types of radiation: radio waves, microwaves, infrared, visible, ultraviolet, X-rays, gamma-rays.
- Gamma-rays have the most energy and are the most penetrating, while radio waves have the lowest energy and are the least penetrating.

Physical Quantities		
Quantity	**Unit name**	**Unit symbol**
Energy (E)	joule	J
Wavelength (λ)	metre	m
Period (T)	second	s
Frequency (f)	hertz	Hz (s^{-1})
Speed of light (c)	metre per second	$\text{m} \cdot \text{s}^{-1}$

Table 11.3: Units used in **electromagnetic radiation**

Chapter 11 End of chapter exercises

1. What is the energy of a photon of EM radiation with a frequency of 3×10^8 Hz?

2. What is the energy of a photon of light with a wavelength of 660 nm?

3. What is the energy of a photon of light with a frequency of 13 THz?

4. What is the wavelength of a photon of light with a frequency of 101.3 kHz?

5. What is the energy of a photon of light with a wavelength of 532 nm and one with a frequency of 13 GHz and which has the longer wavelength?

6. List the main types of electromagnetic radiation in order of increasing wavelength.
7. List the main uses of:
   a. radio waves
   b. infrared
   c. gamma rays
   d. X-rays
8. Explain why we need to protect ourselves from ultraviolet radiation from the Sun.
9. List some advantages and disadvantages of using X-rays.
10. What precautions should we take when using cell phones?
11. Write a short essay on a type of electromagnetic waves. You should look at uses, advantages and disadvantages of your chosen radiation.
12. Explain why some types of electromagnetic radiation are more penetrating than others.

More practice video solutions or help at www.everythingscience.co.za

(1.) 004y (2.) 004z (3.) 01v4 (4.) 01v5 (5.) 01v6 (6.) 0050
(7.) 0051 (8.) 0052 (9.) 0053 (10.) 0054 (11.) 0055 (12.) 0056

The particles that substances are made of 12

Atoms and compounds

The atom as the building block of matter ESADP

We have seen that different materials have different properties. But what would we find if we were to break down a material into the parts that make it up (i.e. it's microscopic structure)? And how is it that this microscopic structure is able to give matter all its different properties?

See introductory video: (Video: VPaxx at www.everythingscience.co.za)

The answer lies in the smallest building block of matter: the **atom**. It is the *type* of atoms, and the way in which they are *arranged* in a material, that affects the properties of that substance. This is similar to building materials. We can use bricks, steel, cement, wood, straw (thatch), mud and many other things to build structures from. The choice of atoms affects the properties of matter in the same way as the choice of building material affects the properties of the structure,

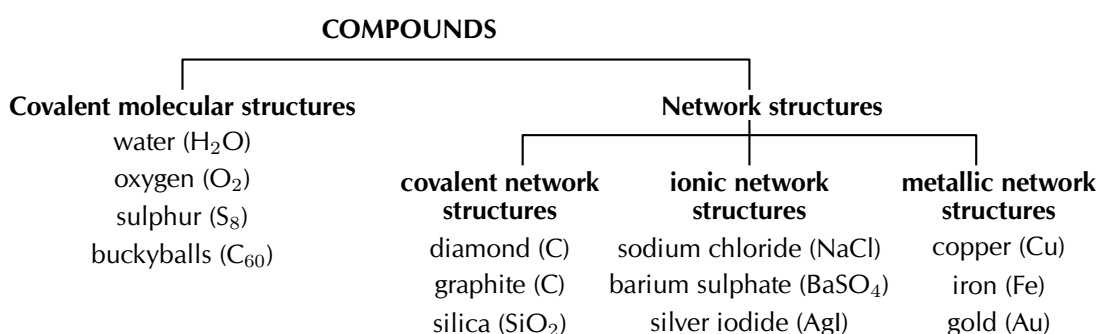
It is not often that substances are found in atomic form (just as you seldom find a building or structure made from one building material). Normally, atoms are bonded (joined) to other atoms to form **compounds** or **molecules**. It is only in the *noble gases* (e.g. helium, neon and argon) that atoms are found individually and are not bonded to other atoms. We looked at some of the reasons for this in earlier chapters.

Compounds

> *DEFINITION: Compound*
>
> A compound is a group of two or more different atoms that are attracted to each other by relatively strong forces or bonds. The atoms are combined in definite proportions.

Compounds can be divided into **molecular compounds** (molecules), **ionic compounds** (salts) and **metallic compounds** (metals).

- **Molecular compounds** form as a result of covalent bonding where electrons are shared between non-metal atoms.
- **Ionic compounds** form as a result of ionic bonding where electrons are transferred from metals to non-metals.
- **Metals** are formed as a result of metallic bonding where metal atoms lose their outer electrons to form a lattice of regularly spaced positive ions and a "pool" of delocalised electrons that surround the positive ions.

The following diagram illustrates how compounds can be subdivided by the type of bonding and the structure:

Covalent molecular structures

Relatively small molecules are called **covalent molecular structures**. These exist and interact as separate molecules. Oxygen (O_2), water (H_2O), octane (C_8H_{18}), sulphur (S_8) and buckminsterfullerene (C_{60}, buckyballs) are all examples of covalent molecular structures.

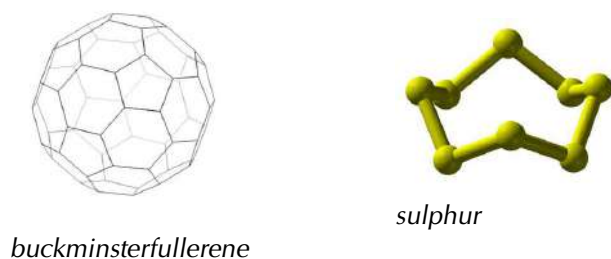



Figure 12.2: Examples of covalent molecular structures

Network structures

Compounds that exist as giant repeating lattice structures are called network structures. Examples include **covalent molecules** such as diamond, graphite and silica. **Ionic substances** are also network structures, for example a sodium chloride crystal is a huge lattice of repeating units made of sodium and chloride ions. All substances formed as a result of ionic bonding are network structures. **Metals** exist as large continuous lattice structures and are also classified as network structures. For example copper, zinc and iron can be seen as a giant crystals and are therefore considered to be network structures. See video: VPazc at www.everythingscience.co.za

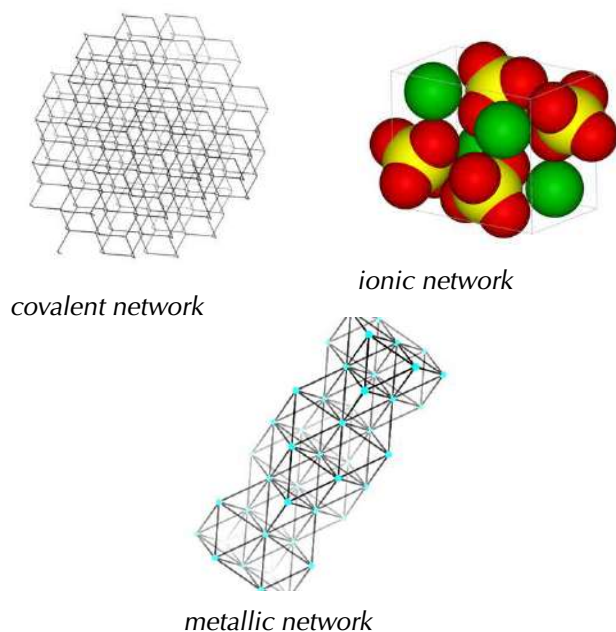



Figure 12.3: Examples of network structures

Representing molecules

ESADR

The structure of a molecule can be shown in many different ways. Sometimes it is easiest to show what a molecule looks like by using different types of **diagrams**, but at other times, we may decide to simply represent a molecule using its **chemical formula** or its written name.

Using formulae to show the structure of a molecule

A **chemical formula** is an abbreviated (shortened) way of describing a compound. In chapter 2, we saw how chemical compounds can be represented using element symbols from the periodic table. A chemical formula can also tell us the *number* of atoms of each element that are in a compound and their *ratio* in that compound. If the compound is a covalent molecular compound then we can use the molecular formula.

> *DEFINITION: Molecular formula*
>
> The molecular formula is a concise way of expressing information about the atoms that make up a particular covalent molecular compound. The molecular formula gives the exact number of each type of atom in the molecule.

Note

The empirical and the molecular formulae can be the same. For example in carbon dioxide the molecular formula is CO_2. This is also the empirical formula since it is the simplest ratio.

For example in figure 12.4 the molecular formula of 2-methyl propane is C_4H_{10}. This tells us that there are 4 carbon atoms and 10 hydrogen atoms in this molecule, i.e the ratio of carbon to hydrogen is $4 : 10$. But we can simplify this ratio to: $2 : 5$. This gives us the **empirical formula** of the molecule.

> *DEFINITION: Empirical formula*
>
> The empirical formula is a way of expressing the *relative* number of each type of atom in a chemical compound. The empirical formula does not show the exact number of atoms, but rather the simplest *ratio* of the atoms in the compound.

The empirical formula is useful when we want to write the formula for *network structures*. Since network structures may consist of millions of atoms, it is impossible to say exactly how many atoms are in each unit. It makes sense then to represent these units using their empirical formula. So, in the case of a metal such as copper, we would simply write Cu, or if we were to represent a unit of sodium chloride, we would simply write NaCl. Chemical formulae (i.e. the molecular or the empirical formula) therefore tell us something about the *types* of atoms that are in a compound and the *ratio* in which these atoms occur in the compound, but they don't give us any idea of what the compound actually looks like, in other words its *shape*. To show the shape of compounds we have to use diagrams. The simplest type of diagram that can be used to describe a compound is its **structural formula**. The structural formula for 2-methyl propane is shown in figure 12.4.

(a) $\mathbf{C_4H_{10}}$ (b) $\mathbf{C_2H_5}$ (c)

```
     CH3
      |
      CH
     /  \
  CH3    CH3
```

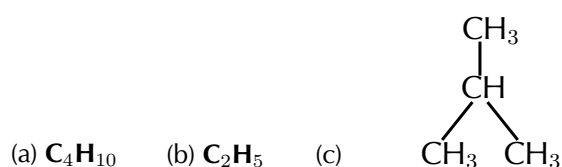



Figure 12.4: Diagram showing (a) the chemical, (b) the empirical and (c) the structural formula of 2-methyl propane

Using diagrams to show the structure of a compound

Diagrams of compounds are very useful because they help us to picture how the atoms are arranged in the compound and they help us to see the shape of the compound. There are three types of diagrams that are commonly used:

- **Wireframe or stick models**
  In this model, the bonds between atoms are shown as "sticks". These "sticks" are coloured to show which atoms are bonding.
- **Ball and stick models**
  This is a 3-dimensional molecular model that uses "balls" to represent atoms and "sticks" to represent the bonds between them. The centres of the atoms (the balls) are connected by straight lines which represent the bonds between them.
- **Space-filling models**
  This is also a 3-dimensional molecular model. The atoms are represented by spheres.

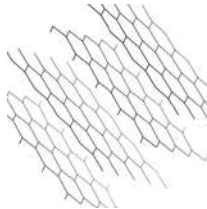
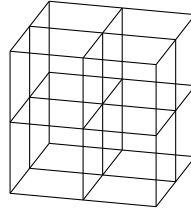
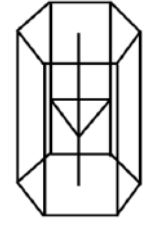
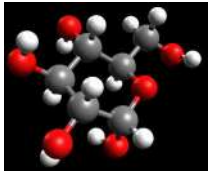
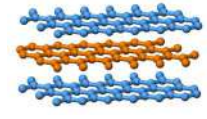
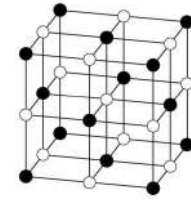
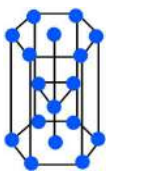
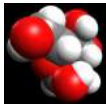
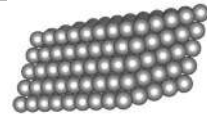
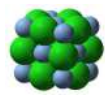
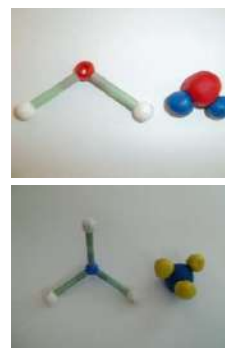
Table 12.1 shows examples of the different types of models for all the types of compounds.

	Covalent molecular	**Covalent network**	**Ionic network**	**Metallic network**
Name of compound	glucose	graphite	silver chloride	zinc
Formula	$C_6H_{12}O_6$ or CH_2O	C	AgCl	Zn
Stick model				
Ball-and-stick model				
Space-filling model				

Table 12.1: Different representations for compounds

Activity: *Representing compounds*

A list of substances is given below. Make use of atomic model kits, play dough and toothpicks, or coloured polystyrene balls and skewer sticks to represent each of the substances in three dimensional structures.

- glucose ($C_6H_{12}O_6$)
- silica (SiO_2)
- sodium chloride (NaCl)
- sulphur (S_8)
- diamond (C)
- graphite (C)
- buckyballs(C_{60})
- sucrose ($C_{12}H_{22}O_{11}$)
- copper (Cu)

See video: VPcbj at www.everythingscience.co.za

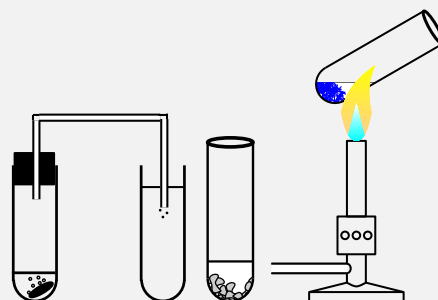
Note

CanvasMol (VPdve) is a website that allows you to view several compounds. You do not need to know these compounds, this is simply to allow you to see one way of representing compounds.

General experiment: *Investigating elements and compounds*

Aim: To investigate three reactions to learn about elements and compounds.

Apparatus:

- Cal-C-Vita tablet
- test tubes
- Bunsen burner
- rubber stopper
- delivery tube
- lime water (a saturated solution of $Ca(OH)_2$)
- candle
- matches
- copper sulphate ($CuSO_4 \cdot 5H_2O$)
- zinc metal
- hydrochloric acid (HCl)

Method:

Reaction 1

1. Pour clear lime water into a test tube.
2. Into a second test tube place a Cal-C-Vita tablet. Cover the tablet with water and immediately place a stopper and delivery tube into the test tube.
3. Place the other end of the delivery tube into the lime water in the first test tube. Allow it to bubble for 1-2 minutes.
4. Now remove the stopper from the second test tube and hold a lit candle at the mouth of the test tube.
5. Record your observations.

Reaction 2

1. Place a few drops of zinc metal in a test tube and cover the pieces with dilute hydrochloric acid.
2. Record your observations.
3. Now hold a burning match in the mouth of the test tube and observe what happens.

Reaction 3

1. Place a spatula full of copper sulphate crystals into a test tube and heat the tube over a Bunsen burner.
2. Record your observations.

Discussion and conclusion: In the first reaction the lime water goes milky due to the presence of carbon dioxide. (Lime water can be used to detect carbon dioxide gas.) The carbon dioxide gas comes from the sodium bicarbonate ($NaHCO_3$) in the tablet. When you hold the candle over the test tube, the carbon dioxide snuffs out the candle flame.

In the second reaction bubbles of hydrogen gas form. Zinc reacts with the hydrochloric acid to form zinc chloride and hydrogen gas.

In the third reaction the copper sulphate crystals go white and droplets of water form on the sides of the test tube. The copper sulphate crystals have lost their water of crystallisation.

See video: VPbec at www.everythingscience.co.za

General experiment: *The electrolysis of water*

Aim: To investigate the elements that make up water.

Apparatus:

- water
- two pencils sharpened at both ends
- 9 volt battery
- connecting wire
- tape
- table salt or sodium sulphate

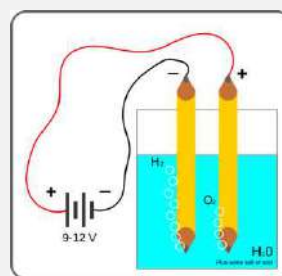



image by Nevit Dilmen

Method: Set up the apparatus as shown above. Observe what happens.

Results: You should observe bubbles forming at the tips of the pencils. Oxygen gas is formed at the positive side and hydrogen at the negative side.

Chapter 12 | Summary

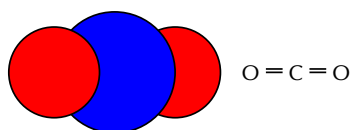
See the summary presentation (Presentation: VPdvy at www.everythingscience.co.za)

- The smallest unit of matter is the **atom**. Atoms can combine to form **compounds**.
- A **compound** is a group of two or more different atoms that are attracted to each other by relatively strong forces or bonds. The atoms are combined in definite proportions.
- In a compound, atoms are held together by **chemical bonds**. Covalent bonds, ionic bonds and metallic bonds are examples of chemical bonds.
- A **covalent bond** exists between non-metal atoms. An **ionic bond** exists between non-metal and metal atoms and a **metallic bond** exists between metal atoms.
- **Covalent molecular structures** interact and exist as separate molecules.
- **Network structures** exist as giant repeating lattices. Network structures can consist of covalent, ionic or metallic compounds.
- A chemical formula is an abbreviated (shortened) way of describing a compound.
- The **molecular formula** is a concise way of expressing information about the atoms that make up a particular covalent molecular compound. The molecular formula gives the exact number of each type of atom in the molecule.
- The **empirical formula** is a way of expressing the relative number of each type of atom in a chemical compound. The empirical formula does not show the exact number of atoms, but rather the simplest ratio of the atoms in the compound.
- The structure of a compound can be represented by stick, ball-and-stick or space-filling models.
- A **stick** model use coloured sticks to represent compounds.
- A **ball-and-stick** model is a 3-dimensional molecular model that uses "balls" to represent atoms and "sticks" to represent the bonds between them.
- A **space-filling model** is also a 3-dimensional molecular model. The atoms are represented by spheres.

Chapter 12 End of chapter exercises

1. Give one word or term for each of the following descriptions.
    a. A composition of two or more atoms that act as a unit.
    b. Chemical formula that gives the relative number of atoms of each element that are in a molecule.
2. Give a definition for each of the following terms:
    a. molecule
    b. ionic compound
    c. covalent network structure

d. empirical formula
   e. ball-and-stick model

3. Ammonia, an ingredient in household cleaners, is made up of one part nitrogen (N) and three parts hydrogen (H). Answer the following questions:
   a. is ammonia a covalent, ionic or metallic substance?
   b. write down the molecular formula for ammonia
   c. draw a ball-and-stick diagram
   d. draw a space-filling diagram
4. In each of the following, say whether the chemical substance is made up of covalent, molecular structures, covalent network structures, ionic network structures or metallic structures:
   a. ammonia gas (NH_3)
   b. zinc metal (Zn)
   c. graphite (C)
   d. nitric acid (HNO_3)
   e. potassium bromide (KBr)
5. Refer to the diagram below and then answer the questions that follow:

   a. Identify the molecule.
   b. Write the molecular formula for the molecule.
   c. Is the molecule a covalent, ionic or metallic substance? Explain.
6. Represent each of the following molecules using its *chemical formula*, *structural formula* and the *ball-and-stick model*.
   a. nitrogen
   b. carbon dioxide
   c. methane
   d. argon

More practice   video solutions   or help at www.everythingscience.co.za

(1.) 01uq   (2.) 01ur   (3.) 01us   (4.) 01ut   (5.) 01uu   (6.) 01uv

Physical and chemical change

13

Introduction

ESADS

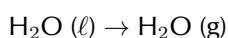
Matter is all around us. The desks we sit at, the air we breathe and the water we drink are all examples of matter. But matter doesn't always stay the same. It can change in many different ways. In this chapter, we are going to take a closer look at **physical** and **chemical** changes that occur in matter.

See introductory video: (Video: VPber at www.everythingscience.co.za)

Physical changes in matter

ESADT

A **physical change** is one where the particles of the substances that are involved in the change are not broken up in any way. When water is heated for example, the temperature and energy of the water molecules increases and the liquid water evaporates to form water vapour. When this happens, some kind of change has taken place, but the molecular structure of the water has not changed. This is an example of a *physical change*. All changes in state are physical changes.

H_2O (ℓ) $\rightarrow$ H_2O (g)

Conduction (the transfer of energy through a material) is another example of a physical change. As energy is transferred from one material to another, the *energy* of each material is changed, but not its chemical makeup. Dissolving one substance in another is also a physical change.

DEFINITION: Physical change

A change that can be seen or felt, but that doesn't involve the break up of the particles in the reaction. During a physical change, the *form* of matter may change, but not its *identity*.

There are some important things to remember about physical changes in matter:

1. *Arrangement of particles* When a physical change occurs, the compounds may re-arrange themselves, but the bonds in between the atoms will not break. For example when liquid water boils, the molecules will move apart but the molecule will stay intact. In other words water will not break up into hydrogen and oxygen atoms.
   Figure 13.1 shows this phase change. Note that the water molecules themselves stay the same, but their arrangement changed.

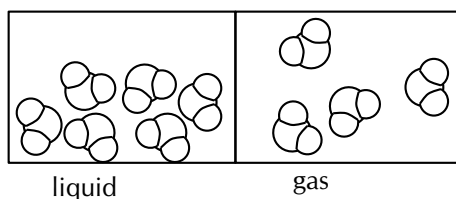



Figure 13.1: The arrangement of water molecules in the liquid and gas phase

2. *Conservation of mass*
   In a physical change, the total mass, the number of atoms and the number of molecules will always stay the same. In other words you will always have the same number of molecules or atoms at the end of the change as you had at the beginning.
3. *Energy changes*
   Energy changes may take place when there is a physical change in matter, but these energy changes are normally smaller than the energy changes that take place during a chemical change.
4. *Reversibility*
   Physical changes in matter are usually easier to reverse than chemical changes. Methods such as filtration and distillation can be used to reverse the change. Changing the temperature is another way to reverse a physical change. For example, a mixture of salt dissolved in water can be separated by filtration, ice can be changed to liquid water and back again by changing the temperature.

FACT

The bonding of hydrogen and oxygen to form water is explosive and if the water molecule broke apart every time water boiled, life on Earth would not exist for very long!

Activity: *Physical change*

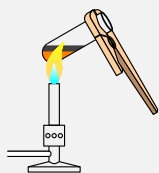
Use plastic pellets or marbles to represent water in the solid state. What do you need to do to the pellets to represent the change from solid to liquid?

Make a mixture of sand and water. Filter this mixture. What do you observe?

Make a mixture of iron filings and sulphur. Can you separate the mixture with a magnet?

General experiment: *The synthesis of iron sulphide*

Aim: To demonstrate the synthesis of iron sulphide from iron and sulphur.

Apparatus: $5,6$ g iron filings and $3,2$ g powdered sulphur; porcelain dish; test tube; Bunsen burner

Method:

1. Measure the quantity of iron and sulphur that you need and mix them in a porcelain dish.
2. Take some of this mixture and place it in the test tube. The test tube should be about one third full.
3. Heat the test tube containing the mixture over the Bunsen burner. Increase the heat if no reaction takes place. Once the reaction begins, you will need to remove the test tube from the flame. Record your observations.
4. Wait for the product to cool before breaking the test tube with a hammer. Make sure that the test tube is rolled in paper before you do this, otherwise the glass will shatter everywhere and you may be hurt.
5. What does the product look like? Does it look anything like the original reactants? Does it have any of the properties of the reactants (e.g. the magnetism of iron)?

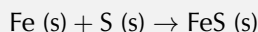
Warning:

When working with a Bunsen burner, work in a well ventilated space and ensure that there are no flammable substances close by. Always tuck loose clothing in and ensure that long hair is tied back.

Results: After you removed the test tube from the flame, the mixture glowed a bright red colour. The reaction is exothermic and *produces heats*. The product, iron sulphide, is a dark colour and does not share any of the properties of the original reactants. It is an entirely new product.

Conclusions: A synthesis reaction has taken place. The equation for the reaction

is:

$$Fe\ (s) + S\ (s) \rightarrow FeS\ (s)$$

Chemical Changes in Matter

When a **chemical change** takes place, new substances are formed in a chemical reaction. These new products may have very different properties from the substances that were there at the start of the reaction.

See video: VPbfo at www.everythingscience.co.za

DEFINITION: Chemical change

The formation of new substances in a chemical reaction. One type of matter is changed into something different.

We will consider two examples of chemical change: the decomposition (breaking down) of hydrogen peroxide and the synthesis (forming) of water.

Decomposition of hydrogen peroxide

The decomposition (breakdown) of hydrogen peroxide (H_2O_2) to form water (H_2O) and oxygen gas (O_2) is an example of chemical change. A simplified diagram of this reaction is shown in Figure 13.2. The chemical bonds between O and H in H_2O_2 are broken and new bonds between H and O (to form H_2O) and between O and O (to form O_2) are formed. A chemical change has taken place.

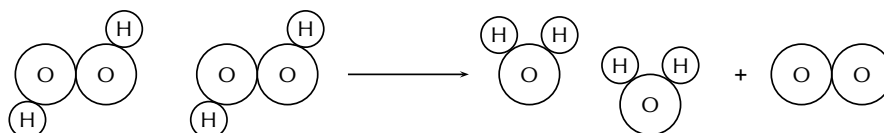
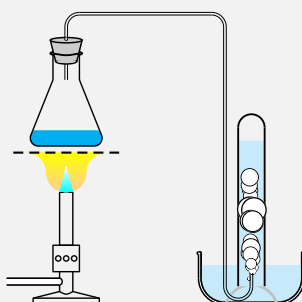



Figure 13.2: The decomposition of H_2O_2 to form H_2O and O_2

General experiment: *The decomposition of hydrogen peroxide*

Aim: To observe the decomposition of hydrogen peroxide when it is heated.

Apparatus: Dilute hydrogen peroxide (about 3%); manganese dioxide; test tubes; a water bowl; stopper and delivery tube, Bunsen burner

Warning:

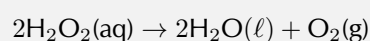
Hydrogen peroxide can cause chemical burns. Work carefully with it.

Method:

1. Put a small amount (about 5 ml) of hydrogen peroxide in a test tube.
2. Set up the apparatus as shown above.
3. Very carefully add a small amount (about $0,5$ g) of manganese dioxide to the test tube containing hydrogen peroxide.

Results: You should observe a gas bubbling up into the second test tube. This reaction happens quite rapidly.

Conclusions: When hydrogen peroxide is added to manganese dioxide it decomposes to form oxygen and water. The chemical decomposition reaction that takes place can be written as follows:

$$2H_2O_2(aq) \rightarrow 2H_2O(\ell) + O_2(g)$$

Note that the manganese dioxide is a catalyst and does not take part in the reac-

tion, so we do not show it in the balanced equation. (A catalyst helps speed up a chemical reaction.)

Note

This experiment used the downward displacement of water to collect a gas. This is a very common way to collect a gas in chemistry. The oxygen that is evolved in this reaction moves along the delivery tube and then collects in the top of the test tube. It does this because it is less dense than water and does not dissolve in water, so the water is displaced downwards.

FACT

This reaction is often performed without collecting the oxygen gas and is commonly known as the elephant's toothpaste reaction.

See video: VPbfq at www.everythingscience.co.za

The above experiment can be very vigorous and produce a lot of oxygen very rapidly. For this reason you should use dilute hydrogen peroxide and only a small amount of manganese dioxide.

The synthesis of water

The synthesis (forming) of water (H_2O) from hydrogen gas (H_2) and oxygen gas (O_2) is another example of chemical change. A simplified diagram of this reaction is shown in figure 13.3. The chemical bonds between O in O_2 and between H in H_2 are broken and new bonds between H and O (to form H_2O) are formed. A chemical change has taken place.

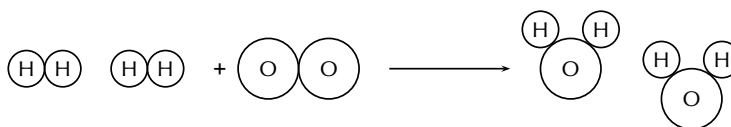



Figure 13.3: The synthesis of H_2O from H_2 and O_2

See video: VPbhy at www.everythingscience.co.za

General experiment: *The synthesis of water*

Aim:
To observe the synthesis of water.

Apparatus:
Hydrogen gas; balloon; string; candle; long stick: ear plugs; safety glasses

photos by argonnenationallaboratory on Flickr.com

Method:

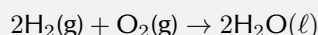
1. Half fill a balloon with hydrogen gas.
2. Fill the remainder of the balloon with oxygen gas. (You can also just use your breath to fill the balloon.)
3. Tie the balloon to one end of the string. Tie down the other end of the string so that the balloon is positioned in mid air, away from any people, objects, walls, ceilings etc.
4. Attach the candle tightly to the stick and light the candle.
5. Standing away from the balloon, carefully hold the candle to the balloon.

Warning:

This reaction can be highly explosive, for this reason it is best done outdoors. Always ensure that you wear ear protection or block your ears. Always have more oxygen than hydrogen in the balloon.

Results:
When you bring the candle close to the balloon you should see a flame and hear a loud bang.

Conclusions:
When a mixture of hydrogen and oxygen gas is set alight with a candle a chemical change occurs. Water is made according to the following equation:

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(\ell)$$

FACT

A mixture of hydrogen and oxygen gas is used as a fuel to get rockets into space.

There are some important things to remember about chemical changes:

1. *Arrangement of particles*
During a chemical change, the particles themselves are changed in some way. In the example of hydrogen peroxide that was used earlier, the H_2O_2 molecules were split up into their component atoms. The number of particles will change because each H_2O_2 molecule breaks down into two water molecules (H_2O) and one oxygen molecule (O_2).
2. *Energy changes*
The energy changes that take place during a chemical reaction are much greater than those that take place during a physical change in matter. During a chemical reaction, energy is used up in order to break bonds and then energy is released when the new

product is formed.

3. *Reversibility*
   Chemical changes are far more difficult to reverse than physical changes. When hydrogen peroxide decomposes into water and oxygen, it is almost impossible to get back to hydrogen peroxide.
4. *Mass conservation*
   Mass is conserved during a chemical change, but the number of molecules may change. In the example of the decomposition of hydrogen peroxide, for every two molecules of hydrogen peroxide that decomposes, three molecules are formed (two water and one oxygen).

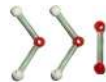
Table 13.1 highlights these concepts for the decomposition of hydrogen peroxide.

	$2H_2O_2 \rightarrow 2H_2O + O_2$	
Molecules	two molecules	three molecules
Energy changes	energy taken in when bonds are broken	energy given off when bonds are formed
Mass is conserved	$4(1,01) + 4(16,0) = 68,04$	$2(18,02) + 2(16,0) = 68,04$
Atoms are conserved	4 oxygen atoms, 4 hydrogen atoms	4 oxygen atoms, 4 hydrogen atoms

Table 13.1: Important concepts in chemical change

Exercise 13 - 1

For each of the following say whether a chemical or a physical change occurs.

1. Melting candle wax.
2. Mixing sodium chloride (NaCl) and silver nitrate ($AgNO_3$) to form silver chloride (AgCl).
3. Mixing hydrochloric acid (HCl) and magnesium ribbon (Mg) to form magnesium chloride ($MgCl_2$).
4. Dissolving salt in water.
5. Tearing a piece of magnesium ribbon.

(1. – 5.) 0057

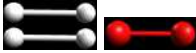
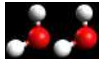
Conservation of atoms and mass in reactions

In a chemical reaction the total mass of all the substances taking part in the reaction remains the same. Also, the number of **atoms** in a reaction remains the same. Mass cannot be created or destroyed in a chemical reaction.

See video: VPbkj at www.everythingscience.co.za

> *DEFINITION: Law of conservation of mass*
>
> The law of conservation of mass states that the total mass of substances taking part in a chemical reaction is conserved during the reaction.

Table 13.1 illustrates this law for the decomposition of hydrogen peroxide.

Activity: *The conservation of atoms in chemical reactions*

We will use the reaction of hydrogen and oxygen to form water in this activity.

Materials: Coloured modelling clay rolled into balls or marbles and prestik to represent atoms. Each colour will represent a different element.

Method:

1. Build your reactants. Use marbles and prestik or modelling clay to represent the reactants and put these on one side of your table. Make at least ten (H_2) units and at least five (O_2) units.
2. Place the H_2 and O_2 units on a table. The table represents the "test tube" where the reaction is going to take place.
3. Now count the number of atoms (H and O) you have in your "test tube". Fill in the reactants column in the table below. Refer to table 13.1 to help you fill in the mass row.
4. Let the reaction take place. Each person can now take the H and O unit and use them to make water units. Break the H and O units apart and build H_2O units with the parts. These are the products. Place the products on the table.

5. When the "reaction" has finished (i.e. when all the H and O units have been used) count the number of atoms (H and O) and complete the table.
6. What do you notice about the number of atoms for the reactants, compared to the products?
7. Write a balanced equation for this reaction and use your models to build this equation.

	Reactants	Products
Number of molecules		
Mass		
Number of atoms		

Discussion: You should have noticed that the number of atoms in the reactants is the same as the number of atoms in the product. The number of atoms is conserved during the reaction. However, you will also see that the number of molecules in the reactants and products are not the same. The number of molecules is not conserved during the reaction.

Informal experiment: *Conservation of matter*

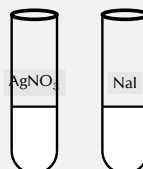
Aim: To prove the law of conservation of matter experimentally.

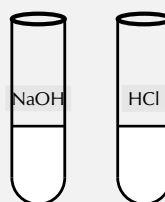
Materials:
Reaction 1:
3 beakers; silver nitrate; sodium iodide; mass meter
Reaction 2:
hydrochloric acid; bromothymol blue; sodium hydroxide solution; mass meter
Reaction 3:
any effervescent tablet (e.g. Cal-C-Vita tablet), balloon; rubber band; mass meter; test tube; beaker

Warning:

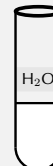
Always be careful when handling chemicals (particularly strong acids like hydrochloric acid) as you can burn yourself badly.

Method:
Reaction 1

1. Solution 1: In one of the beakers dissolve 5 g of silver nitrate in 100 ml of water.
2. Solution 2: In a second beaker, dissolve 4.5 g of sodium iodide in 100 ml of water.
3. Determine the mass of each of the reactants.
4. Add solution 1 to solution 2. What do you observe? Has a chemical reaction taken place?
5. Determine the mass of the products.
6. What do you notice about the masses?
7. Write a balanced equation for this reaction.

Reaction 2:

1. Solution 1: Dissolve 0.4 g of sodium hydroxide in 100 ml of water. Add a few drops of bromothymol blue indicator to the solution.
2. Solution 2: Measure 100 ml of 0, 1 M hydrochloric acid solution into a second beaker.
3. Determine the mass of the reactants.
4. Add small quantities of solution 2 to solution 1 (you can use a plastic pipette for this) until a colour change has taken place. Has a chemical reaction taken place?
5. Determine the mass of hydrochloric acid added. (You do this by weighing the remaining solution and subtracting this from the starting mass)
6. Compare the mass before the reaction to the total mass after the reaction. What do you notice?
7. Write a balanced equation for this reaction.

Reaction 3

1. Half fill a large test tube with water.
2. Determine the mass of the test tube and water.
3. Break an effervescent tablet in two or three pieces and place them in a balloon.
4. Determine the mass of the balloon and tablet.
5. Fit the balloon tightly to the test tube, being careful to not drop the contents into the water. You can stand the test tube in a beaker to help you do this.
6. Determine the total mass of the test tube and balloon.
7. Lift the balloon so that the tablet goes into the water. What do you observe? Has a chemical reaction taken place?
8. Determine the mass of the test tube balloon combination.
9. What do you observe about the masses before and after the reaction?

H_2O

Results: Fill in the following table for the total mass of reactants (starting materials) and products (ending materials).

	Reaction 1	Reaction 2	Reaction 3
Reactants			
Products			

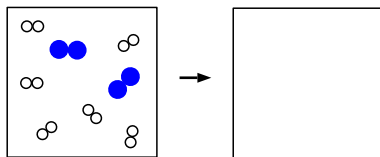
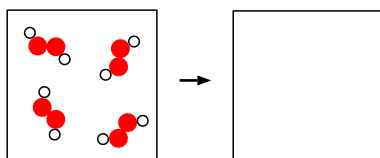
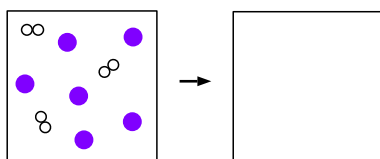
Add the masses for the reactants for each reaction. Do the same for the products. For each reaction compare the mass of the reactants to the mass of the products. What do you notice? Is the mass conserved?

In the experiment above you should have found that the total mass at the start of the reaction is the same as the mass at the end of the reaction. Mass does not appear or disappear in chemical reactions. Mass is conserved, in other words, the total mass you start with is the total mass you will end with.

Exercise 13 - 2

Complete the following chemical reactions to show that atoms and mass are

conserved. For each reaction give the total molecular mass of the reactants and the products.

1. Hydrogen gas combines with nitrogen gas to form ammonia.

2. Hydrogen peroxide decomposes (breaks down) to form hydrogen and oxygen.

3. Calcium and oxygen gas react to form calcium oxide.

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(1.) 0058 (2.) 0059 (3.) 005a

Law of constant composition

ESADW

In any given chemical compound, the elements always combine in the same proportion with each other. This is the **law of constant composition**.

The **law of constant composition** says that, in any particular chemical compound, all samples of that compound will be made up of the same elements in the same proportion or ratio. For example, any water molecule is always made up of two hydrogen atoms and one oxygen atom in a $2:1$ ratio. If we look at the relative masses of oxygen and hydrogen in

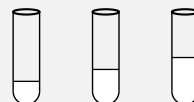
a water molecule, we see that 94% of the mass of a water molecule is accounted for by oxygen and the remaining 6% is the mass of hydrogen. This mass proportion will be the same for any water molecule.

This does not mean that hydrogen and oxygen always combine in a $2:1$ ratio to form H_2O. Multiple proportions are possible. For example, hydrogen and oxygen may combine in different proportions to form H_2O_2 rather than H_2O. In H_2O_2, the H : O ratio is $1:1$ and the mass ratio of hydrogen to oxygen is $1:16$. This will be the same for any molecule of hydrogen peroxide.

Investigation: *Law of constant composition*

Aim: To investigate the ratio in which compounds combine.

Apparatus:

- $0,1$ M silver nitrate ($AgNO_3$)
- $0,1$ M sodium chloride ($NaCl$)
- $0,1$ M lead nitrate ($PbNO_3$)
- $0,1$ M sodium iodide (NaI)
- $0,1$ M iron (III) chloride ($FeCl_3$)
- $0,1$ M sodium hydroxide ($NaOH$)
- 9 large test tubes
- 3 propettes

Method:

Reaction 1: Prepare three test tubes with 5 ml, 10 ml and 15 ml of silver nitrate respectively. Using a clean propette add 5 ml of sodium chloride to each one and observe what happens.

Reaction 2: Prepare three test tubes with 5 ml, 10 ml and 15 ml of lead nitrate respectively. Using a clean propette add 5 ml of sodium iodide to each one and observe what happens. Write a balanced equation for this reaction.

Reaction 3: Prepare three test tubes with 5 ml, 10 ml and 15 ml of sodium hydroxide respectively. Add 5 ml of iron(III) chloride to each one and observe what happens.

Discussion and conclusion: Regardless of the amount of reactants added, the same products, with the same compositions, are formed (i.e. the precipitate observed in the reactions). However, if the reactants are not added in the correct ratios, there will be unreacted reactants that

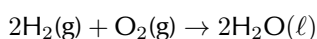
will remain in the final solution, together with the products formed.

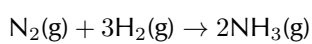
Volume relationships in gases

ESADX

In a chemical reaction between gases, the relative volumes of the gases in the reaction are present in a ratio of small whole numbers if all the gases are at the same temperature and pressure. This relationship is also known as **Gay-Lussac's Law**.

For example, in the reaction between hydrogen and oxygen to produce water, two volumes of H_2 react with 1 volume of O_2 to produce 2 volumes of H_2O.

$2H_2(g) + O_2(g) \rightarrow 2H_2O(\ell)$

In the reaction to produce ammonia, one volume of nitrogen gas reacts with three volumes of hydrogen gas to produce two volumes of ammonia gas.

$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$

Chapter 13 | Summary

See the summary presentation (Presentation: VPdwh at www.everythingscience.co.za)

- Matter does not stay the same. It may undergo physical or chemical changes.
- A **physical change** is a change that can be seen or felt, but that does not involve the break up of the particles in the reaction. During a physical change, the form of matter may change, but not its identity.
- During a physical change, the **arrangement of particles** may change but the mass, number of atoms and number of molecules will stay the same.
- Physical changes involve small changes in **energy** and are easily reversible.
- A chemical change occurs when one or more substances change into other materials. A chemical reaction involves the formation of new substances with **different properties**. For example, hydrogen and oxygen react to form water
- A chemical change may involve a **decomposition** or **synthesis** reaction. During a chemical change, the mass and number of atoms is conserved, but the number of

molecules is not always the same.

- Chemical reactions involve large changes in energy. Chemical reactions are not easily reversible.
- The **law of conservation of mass** states that the total mass of all the substances taking part in a chemical reaction is conserved and the number of atoms of each element in the reaction does not change when a new product is formed.
- The **law of constant composition** states that in any particular compound, all samples of that compound will be made up of the same elements in the same proportion or ratio.
- **Gay-Lussac's Law** states that in a chemical reaction between gases, the relative volumes of the gases in the reaction are present in a ratio of small whole numbers if all the gases are at the same temperature and pressure.

Chapter 13 End of chapter exercises

1. For each of the following definitions give one word or term:
   a. A change that can be seen or felt, where the particles involved are not broken up in any way
   b. The formation of new substances in a chemical reaction
   c. A reaction where a new product is formed from elements or smaller compounds
2. Explain how a chemical change differs from a physical change.
3. Complete the following table by saying whether each of the descriptions is an example of a physical or chemical change:

Description	Physical or chemical
hot and cold water mix together	
milk turns sour	
a car starts to rust	
food digests in the stomach	
alcohol disappears when it is placed on your skin	
warming food in a microwave	
separating sand and gravel	
fireworks exploding	

4. For each of the following reactions, say whether it is an example of a synthesis or decomposition reaction:

a. $(NH_4)_2 CO_3 \rightarrow NH_3 + CO_2 + H_2O$
b. $N_2 (g) + 3H_2 (g) \rightarrow 2NH_3(g)$
c. $CaCO_3 \rightarrow CaO + CO_2$

5. For the following equation: $CaCO_3 (s) \rightarrow CaO + CO_2$ show that the law of conservation of mass applies. Draw sub-microscopic diagrams to represent this reaction.

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(1.) 005b (2.) 005c (3.) 005d (4.) 005e (5.) 005f

Representing chemical change 14

Introduction

As we have already mentioned, a number of changes can occur when elements are combined with one another. These changes may either be *physical* or *chemical*. In this chapter we will look at chemical changes. One way of representing chemical changes is through **balanced chemical equations**. A chemical equation describes a chemical reaction by using symbols for the elements involved. For example, if we look at the reaction between iron (Fe) and sulphur (S) to form iron sulphide (FeS), we could represent these changes in a sentence, in a word equation or using chemical symbols:

> **Sentence:** Iron reacts with sulphur to form iron sulphide. **Word equation:** Iron + sulphur → iron sulphide. **Chemical symbols:** $Fe + S \rightarrow FeS$

Another example would be:

> **Sentence:** Ammonia reacts with oxygen to form nitrogen monoxide and water. **Word equation:** Ammonia + oxygen → nitrogen monoxide + water. **Chemical symbols:** $4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$

See introductory video: (Video: VPbkm at www.everythingscience.co.za)

Compounds on the left of the arrow are called the **reactants** and these are needed for the reaction to take place. The compounds on the right are called the **products** and these are what is formed from the reaction.

In order to be able to write a balanced chemical equation, there are a number of important things that need to be done:

1. Know the chemical symbols for the elements involved in the reaction
2. Be able to write the chemical formulae for different reactants and products
3. Balance chemical equations by understanding the laws that govern chemical change
4. Know the state symbols for the equation

We will look at each of these steps separately in the next sections.

Chemical symbols

 ESADZ

It is very important to know the chemical symbols for common elements in the periodic table, so that you are able to write chemical equations and to recognise different compounds.

Activity: *Revising common chemical symbols*

- Write down the chemical symbols and names of all the elements that you know.
- Compare your list with another learner and add any symbols and names that you don't have.
- Know the symbols for at least the first thirty six elements in the periodic table. You should also learn the symbols for other common elements that are not in the first thirty six.
- Set a short test on naming elements and compounds for someone else in the class and then exchange tests with them so that you each have the chance to answer a test.

Writing chemical formulae

ESAEA

A **chemical formula** is a concise way of giving information about the atoms that make up a particular chemical compound. A chemical formula shows each element by its symbol and also shows how many atoms of each element are found in that compound. The number of atoms (if greater than one) is shown as a subscript.

The following exercise serves as revision. If you do not recall how to write chemical formulae refer back to chapter 2.

Exercise 14 - 1

1. Write down the chemical formula for each of the following compounds:

   a. iron (III) chloride
   b. zinc nitrate
   c. aluminium sulphate
   d. calcium hydroxide
   e. magnesium carbonate
   f. the product when carbon reacts with oxygen
   g. the product when hydrogen reacts with nitrogen
   h. potassium oxide
   i. copper (II) bromide
   j. potassium dichromate

2. Write down the name for each of the following compounds:

   a. SO_2
   b. $KMnO_4$
   c. $(NH_4)_2SO_4$
   d. BaF_2
   e. $Cr(HSO_4)_3$
   f. CH_4

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(1.) 02u2 (2.) 02u3

Balancing chemical equations ESAEB

The law of conservation of mass ESAEC

In order to balance a chemical equation, it is important to understand the law of conservation of mass.

DEFINITION: The law of conservation of mass

The mass of a closed system of substances will remain constant, regardless of the processes acting inside the system. Matter can change form, but cannot be created or destroyed.

Tip

Iron is a metal. When we represent it in a balanced chemical equation, we write only Fe. Sulphur occurs as S_8 but we write only the empirical formula: S. We do this for all network structures. Writing formulae like this represents *one unit* of the compound or network structure.

For any chemical equation (in a closed system) the **mass** of the reactants must be equal to the mass of the products. In order to make sure that this is the case, the number of **atoms** of each element in the reactants must be equal to the number of atoms of those same elements in the products. An example is shown below:

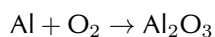
$Fe + S \rightarrow FeS$		
Mass of one atom of Fe is $55,8$	Mass of one atom of S is $32,1$	Mass of one atom of FeS is $87,9$
Mass of reactants is $87,9$		Mass of products is $87,9$

To calculate the **mass of the molecules** we use the relative atomic masses for iron and sulphur, as seen in table 14.2. You will notice that the mass of the reactants equals the mass of the product. A chemical equation that is **balanced** will always reflect the **law of conservation of mass** and the **law of conservation of atoms**.

Activity: *Balancing chemical equations*

1. You will need: coloured balls (or marbles), prestik, a sheet of paper and coloured pens.

We will try to balance the following equation:

$$Al + O_2 \rightarrow Al_2O_3$$

Take one ball of one colour. This represents a molecule of Al. Take two balls of another colour and stick them together. This represents a molecule of O_2. Place these molecules on your left. Now take two balls of the first colour and three balls of the second colour to form Al_2O_3. Place this compound on your right. On a piece of paper draw coloured circles to represent the balls. Draw a line down the centre of the paper to represent the molecules on the left and on the right.

Count the number of balls on the left and the number on the right. Do you

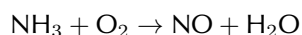
have the same number of each colour on both sides? If not, the equation is not balanced. How many balls of each colour will you have to add to each side to make the number of balls the same? How would you add these balls?

You should find that you need four balls of the first colour for Al and three pairs of balls of the second colour (i.e. six balls in total) for O_2 on the left side. On the right side you should find that you need 2 clusters of balls for Al_2O_3. We say that the balanced equation is:

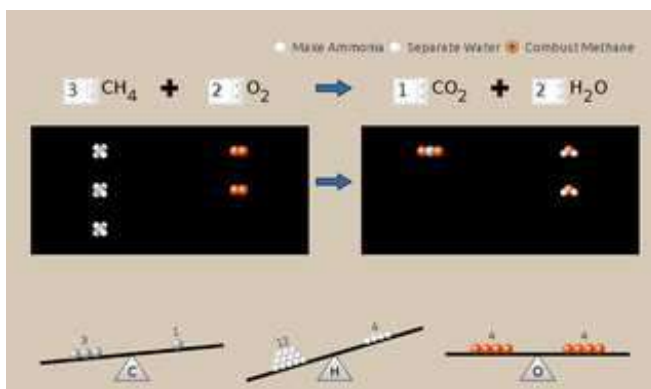
$4Al + 3O_2 \rightarrow 2Al_2O_3$ **2.** Use jelly tots and toothpicks to build the following chemical equation. Make sure that your atoms are balanced. Use the same colour jelly tots for the same atoms.

$C + H_2O \rightarrow CO_2 + CO + H_2$

Add compounds until the atoms are balanced. Write the equation down and use a coefficient to indicate how many compounds you used. For example if you had to use three water molecules then write $3H_2O$ **3** Use ball and stick drawings to balance the atoms in the following reaction:

$NH_3 + O_2 \rightarrow NO + H_2O$

Use your drawings to write a balanced chemical equation for the reaction.

4 Lead (Pb), lead (IV) oxide (PbO_2) and sulphuric acid (H_2SO_4) are used in car batteries. The following reaction takes place: $Pb + PbO_2 + H_2SO_4 \rightarrow PbSO_4 + H_2O$

Cut out circles from four different colours of paper to represent each of the atoms. Build a few of the compounds (Pb PbO_2 H_2SO_4). These are the reactants. Do not build the products. Rearrange the atoms so that the products are formed. Add more reactants if needed to balance the atoms (e.g. you will need two H_2SO_4 molecules). Use what you have learnt to write a balanced equation for the reaction.

Steps to balance a chemical equation through inspection

When balancing a chemical equation, there are a number of steps that need to be followed.

Step 1: Identify the reactants and the products in the reaction and write their chemical formulae.

Step 2: Write the equation by putting the reactants on the left of the arrow and the products on the right.

Step 3: Count the number of atoms of each element in the reactants and the number of atoms of each element in the products.

Step 4: If the equation is not balanced, change the coefficients of the molecules until the number of atoms of each element on either side of the equation balance.

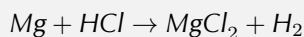
Step 5: Check that the atoms are in fact balanced.

Step 6: (we will look at this a little later): Add any extra details to the equation e.g. phase symbols.

Example 1: *Balancing chemical equations 1*

QUESTION

Balance the following equation:

$$Mg + HCl \rightarrow MgCl_2 + H_2$$

SOLUTION

Step 1 : ***Identify the reactants and products***

This has been done in the question.

Step 2 : ***Write the equation for the reaction***

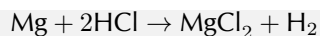
This has been done in the question.

Step 3 : ***Count the number of atoms of each element in the reactants and products***

Reactants: Mg = 1 atom; H = 1 atom; Cl = 1 atom
Products: Mg = 1 atom; H = 2 atoms; Cl = 2 atoms

Step 4 : ***Balance the equation***

The equation is not balanced since there are two chlorine atoms in the product and only one in the reactants. If we add a coefficient of two to the HCl to increase the number of H and Cl atoms in the reactants, the equation will look like this:

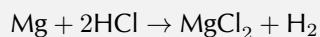
$$Mg + 2HCl \rightarrow MgCl_2 + H_2$$

Step 5 : ***Check that the atoms are balanced***

If we count the atoms on each side of the equation, we find the following:

Reactants: Mg = 1; H = 2; Cl = 2

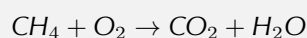
Products: Mg = 1; H = 2; Cl = 2

The equation is balanced. The final equation is:

$$Mg + 2HCl \rightarrow MgCl_2 + H_2$$

Example 2: *Balancing chemical equations 2*

QUESTION

Balance the following equation:

$$CH_4 + O_2 \rightarrow CO_2 + H_2O$$

SOLUTION

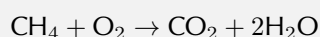
Step 1 : ***Count the number of atoms of each element in the reactants and products***

Reactants: C = 1; H = 4; O = 2

Products: C = 1; H = 2; O = 3

Step 2 : ***Balance the equation***

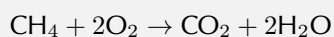
If we add a coefficient of 2 to H_2O, then the number of hydrogen atoms in the products will be 4, which is the same as for the reactants. The equation will be:

$$CH_4 + O_2 \rightarrow CO_2 + 2H_2O$$

Step 3 : ***Check that the atoms balance***

Reactants: C = 1; H = 4; O = 2

Products: C $= 1$; H $= 4$; O $= 4$

You will see that, although the number of *hydrogen* atoms now balances, there are more oxygen atoms in the products. You now need to repeat the previous step. If we put a coefficient of 2 in front of O_2, then we will increase the number of oxygen atoms in the reactants by 2. The new equation is:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

When we check the number of atoms again, we find that the number of atoms of each element in the reactants is the same as the number in the products. The equation is now balanced.

Example 3: *Balancing chemical equations 3*

QUESTION

In our bodies, sugar ($C_6H_{12}O_6$) reacts with the oxygen we breathe in to produce carbon dioxide, water and energy. Write the balanced equation for this reaction.

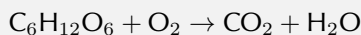
SOLUTION

Step 1 : ***Identify the reactants and products in the reaction.***

Reactants: sugar ($C_6H_{12}O_6$) and oxygen (O_2)

Products: carbon dioxide (CO_2) and water (H_2O)

Step 2 : ***Write the equation***

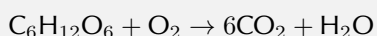
$C_6H_{12}O_6 + O_2 \rightarrow CO_2 + H_2O$

Step 3 : ***Count the number of atoms of each element in the reactants and in the products***

Reactants: C $= 6$; H $= 12$; O $= 8$

Products: C $= 1$; H $= 2$; O $= 3$

Step 4 : ***Balance the equation***

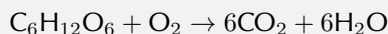
It is easier to start with carbon as it only appears once on each side. If we add a 6 in front of CO_2, the equation looks like this:

$C_6H_{12}O_6 + O_2 \rightarrow 6CO_2 + H_2O$

Reactants: C $= 6$; H $= 12$; O $= 8$

Products: $C = 6;\ H = 2;\ O = 13$

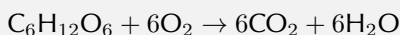
Step 5 : ***Change the coefficients again to try to balance the equation.***

Let us try to get the number of hydrogens the same this time.

$C_6H_{12}O_6 + O_2 \rightarrow 6CO_2 + 6H_2O$

Reactants: $C = 6;\ H = 12;\ O = 8$

Products: $C = 6;\ H = 12;\ O = 18$

Step 6 : ***Now we just need to balance the oxygen atoms.***

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

Reactants: $C = 6;\ H = 12;\ O = 18$

Products: $C = 6;\ H = 12;\ O = 18$

See simulation: (Simulation: VPeea at www.everythingscience.co.za)

Exercise 14 - 2

Balance the following equations:

1. $Mg + O_2 \rightarrow MgO$
2. $Ca + H_2O \rightarrow Ca(OH)_2 + H_2$
3. $CuCO_3 + H_2SO_4 \rightarrow CuSO_4 + H_2O + CO_2$
4. $CaCl_2 + Na_2CO_3 \rightarrow CaCO_3 + NaCl$
5. $C_{12}H_{22}O_{11} + O_2 \rightarrow H_2O + CO_2$
6. Barium chloride reacts with sulphuric acid to produce barium sulphate and hydrochloric acid.
7. Ethane (C_2H_6) reacts with oxygen to form carbon dioxide and steam.
8. Ammonium carbonate is often used as a smelling salt. Balance the following reaction for the decomposition of ammonium carbonate: $(NH_4)_2CO_3(s) \rightarrow NH_3(aq) + CO_2(g) + H_2O(\ell)$
9. Hydrogen fuel cells are extremely important in the development of alternative energy sources. Many of these cells work by reacting hydrogen and oxygen gases together to form water, a reaction which also produces electricity. Balance the following equation: $H_2(g) + O_2(g) \rightarrow H_2O(\ell)$
10. The synthesis of ammonia (NH_3), made famous by the German chemist Fritz Haber in the early 20th century, is one of the most important reactions in the chemical industry. Balance the following equation used to produce ammonia: $N_2(g) + H_2(g) \rightarrow NH_3(g)$

More practice video solutions or help at www.everythingscience.co.za

(1.) 005g (2.) 005h (3.) 005i (4.) 005j (5.) 005k (6.) 005m

(7.) 005n (8.) 005p (9.) 005q (10.) 005r

State symbols and other information *ESAEE*

The state (phase) of compounds can be expressed in the chemical equation. This is done by placing the correct label on the right hand side of the formula. The following four labels can be used:

1. (g) for gaseous compounds
2. (ℓ) for liquids
3. (s) for solid compounds
4. (aq) for an aqueous (water) solution

To show that heat is needed for a reaction, a Greek delta (Δ) is placed above the arrow. For example: $NH_4Cl \xrightarrow{\Delta} NH_3 + HCl$

Example 4: *Balancing chemical equations 4*

QUESTION

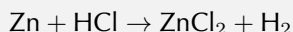
Solid zinc metal reacts with aqueous hydrochloric acid to form an aqueous solution of zinc chloride ($ZnCl_2$) and hydrogen gas. Write a balanced equation for this reaction.

SOLUTION

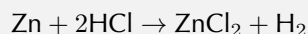
Step 1 : ***Identify the reactants and products***

The reactants are zinc (Zn) and hydrochloric acid (HCl). The products are zinc chloride ($ZnCl_2$) and hydrogen (H_2).

Step 2 : ***Write the equation***

$Zn + HCl \rightarrow ZnCl_2 + H_2$

Step 3 : ***Balance the equation***

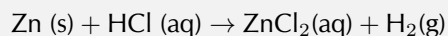
You will notice that the zinc atoms balance but the chlorine and hydrogen atoms do not. Since there are two chlorine atoms on the right and only one on the left, we will give HCl a coefficient of 2 so that there will be two chlorine atoms on each side of the equation.

$Zn + 2HCl \rightarrow ZnCl_2 + H_2$

Step 4 : ***Check that all the atoms balance***

When you look at the equation again, you will see that all the atoms are now balanced.

Step 5 : ***Ensure all details (e.g. state symbols) are added***

In the initial description, you were told that zinc was a metal, hydrochloric acid and zinc chloride were in aqueous solutions and hydrogen was a gas.

$Zn\ (s) + HCl\ (aq) \rightarrow ZnCl_2(aq) + H_2(g)$

See video: VPemn at www.everythingscience.co.za

Exercise 14 - 3

Write balanced equations for each of the following reactions, include state symbols:

1. Lead (II) nitrate solution reacts with a potassium iodide solution to form a precipitate (solid) of lead iodide while potassium nitrate remains in solution.
2. When heated, aluminium metal reacts with solid copper oxide to produce copper metal and aluminium oxide (Al_2O_3).
3. When calcium chloride solution is mixed with silver nitrate solution, a white precipitate (solid) of silver chloride appears. Calcium nitrate ($Ca(NO_3)_2$) is also produced in the solution.
4. Solid ammonium carbonate decomposes to form three gaseous products.

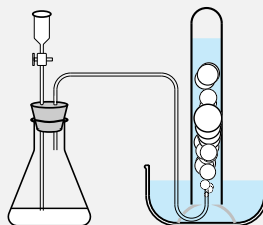
More practice video solutions or help at www.everythingscience.co.za

(1.) 00b7 (2.) 00b8 (3.) 00b9 (4.) 00ba

General experiment: *The relationship between product and reactant*

Aim: To investigate the relationship between the amount of product and the amount of reactant.

Apparatus:

- flask
- measuring cylinder
- water bowl
- delivery tube
- funnel with stopcock
- stopper
- sodium hydrogen carbonate ($NaHCO_3$) powder
- dilute sulphuric acid (H_2SO_4)

Method:

1. Weigh 20 g of $NaHCO_3$ and place it into a flask.
2. Set up the above apparatus.
3. Measure out 5 ml of H_2SO_4 and carefully pour this into the funnel (make sure that the stopcock is closed).
4. Slowly add the H_2SO_4 to the $NaHCO_3$ by opening the stopcock.
5. Observe what happens.
6. Record the volume of gas collected in the measuring cylinder.
7. Repeat the above steps but this time use 10 ml of H_2SO_4.
8. Write a balanced equation for this reaction. (Hint: carbon dioxide gas is formed, as well as water and sodium sulphate.)

Results and discussion: You should observe that more gas is formed when using more H_2SO_4.

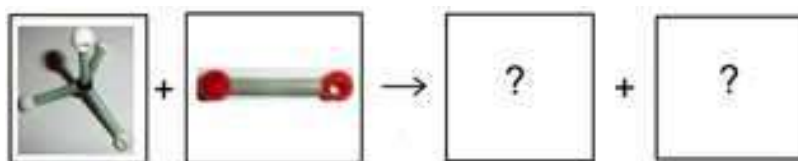
Chapter 14 | Summary

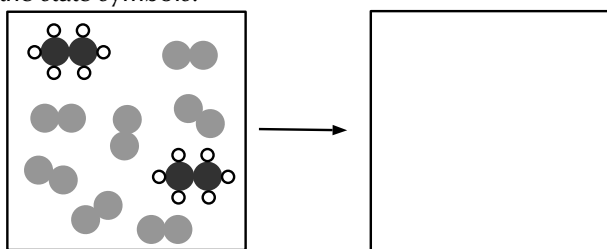
See the summary presentation (Presentation: VPeca at www.everythingscience.co.za)

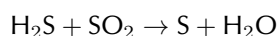
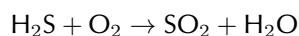
- A **chemical equation** uses symbols to describe a chemical reaction.
- In a chemical equation, **reactants** are written on the left hand side of the equation and the **products** on the right. The arrow is used to show the direction of the reaction.

- When representing chemical change, it is important to be able to write the **chemical formula** of a compound.
- The law of conservation of mass states that the mass of a closed system of substances will remain constant, regardless of the processes acting inside the system. Matter can change form, but cannot be created or destroyed.
- In any chemical reaction, the **law of conservation of mass** applies. This means that the total atomic mass of the reactants must be the same as the total atomic mass of the products. This also means that the total number of atoms of the reactants must be the same as the total number of atoms of the product.
- If the number of atoms of each element in the reactants is the same as the number of atoms of each element in the product, then the equation is **balanced**.
- If the number of atoms of each element in the reactants is not the same as the number of atoms of each element in the product, then the equation is **not balanced**.
- In order to balance an equation, **coefficients** can be placed in front of the reactants and products until the number of atoms of each element is the same on both sides of the equation.
- The state of the compounds in a chemical reaction can be expressed in the chemical equation by using one of four symbols. The symbols are g (gas), ℓ (liquid), s (solid) and aq (aqueous solutions). These symbols are written in brackets after the compound.

Chapter 14 End of chapter exercises

1. Propane is a fuel that is commonly used as a heat source for engines and homes. Balance the following equation for the combustion of propane: $C_3H_8(\ell) + O_2(g) \rightarrow CO_2(g) + H_2O(\ell)$
2. Methane (CH_4) burns in oxygen according to the following reaction.

a. Complete the diagrams by drawing ball-and-stick models of the products.
b. Write a balanced chemical equation for the reaction and include state symbols.

3. Chemical weapons were banned by the Geneva Protocol in 1925. According to this protocol, all chemicals that release suffocating and poisonous gases are not to be used as weapons. White phosphorus, a very reactive allotrope of phosphorus, was recently used during a military attack. Phosphorus burns vigorously in oxygen. Many people got severe burns and some died as a result. The equation for this spontaneous reaction is: $P_4\ (s) + O_2\ (g) \rightarrow P_2O_5\ (s)$
   a. Balance the chemical equation.
   b. Prove that the law of conservation of mass is obeyed during this chemical reaction.
   c. Name the product formed during this reaction.
   d. Classify the reaction as a synthesis or decomposition reaction. Give a reason for your answer.
4. The following diagrams represent the combustion of ethane (C_2H_6). Complete the diagrams and write a balanced equation for the reaction. Indicate the state symbols.

5. Balance the following chemical equation:
   $N_2O_5 \rightarrow NO_2 + O_2$
   Draw submicroscopic diagrams to represent this reaction.
6. Sulphur can be produced by the Claus process. This two-step process involves reacting hydrogen sulphide with oxygen and then reacting the sulphur dioxide that is produced with more hydrogen sulphide. The equations for these two reactions are:

$$H_2S + O_2 \rightarrow SO_2 + H_2O$$
$$H_2S + SO_2 \rightarrow S + H_2O$$

   Balance these two equations.
7. Aspartame, an artificial sweetener, has the formula $C_{14}H_{18}N_2O_2$. Write the balanced equation for its combustion (reaction with O_2) to form CO_2 gas, liquid H_2O, and N_2 gas.

  or help at www.everythingscience.co.za

(1.) 005s (2.) 005t (3.) 005u (4.) 005v (5.) 005w (6.) 005x (7.) 005y

Magnetism

15

Introduction

ESAEF

Magnetism is an interaction that allows certain kinds of objects, which are called 'magnetic' objects, to exert forces on each other without physically touching. A magnetic object is surrounded by a magnetic 'field' that gets weaker as one moves further away from the object. A second object can feel a magnetic force from the first object because it feels the magnetic field of the first object. The further away the objects are the weaker the magnetic force will be.
See introductory video: (Video: VPfkk at www.everythingscience.co.za)
Humans have known about magnetism for many thousands of years. For example, *lodestone* is a magnetised form of the iron oxide mineral *magnetite*. It has the property of attracting iron objects. It is referred to in old European and Asian historical records; from around 800 BCE in Europe and around 2 600 BCE in Asia.

Magnetic objects stuck to a magnet

Photograph by dougww on Flickr.com

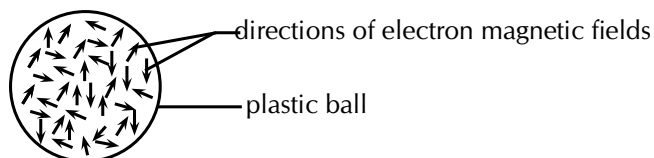
FACT

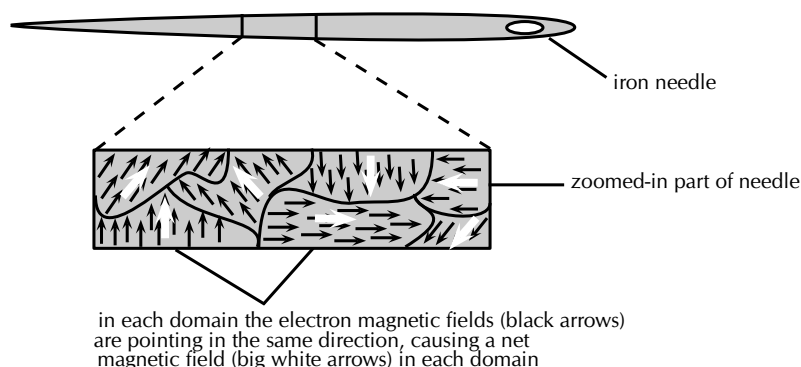
The root of the English word *magnet* is from the Greek word *magnes*, probably from Magnesia in Asia Minor, once an important source of lodestone.

Magnetic fields

A magnetic field is a region in space where a magnet or object made of magnetic material will experience a non-contact, magnetic force.

A moving charged particle has a magnetic fields associated with it. One example of a charged particle that occurs in most matter is the electron. Electrons are in constant motion inside material, orbiting the nucleus in the atom which may also be moving, rotating or vibrating.

So electrons inside any object are moving and have magnetic fields associated with them. In most materials these fields point in various directions, so the net magnetic field is zero. For example, in the plastic ball below, the directions of the magnetic fields of the electrons (shown by the arrows) are pointing in different directions and cancel each other out. Therefore the plastic ball is not magnetic and has no magnetic field.

The electron magnetic fields point in all directions
and so there is no net (total) magnetic field for the whole ball

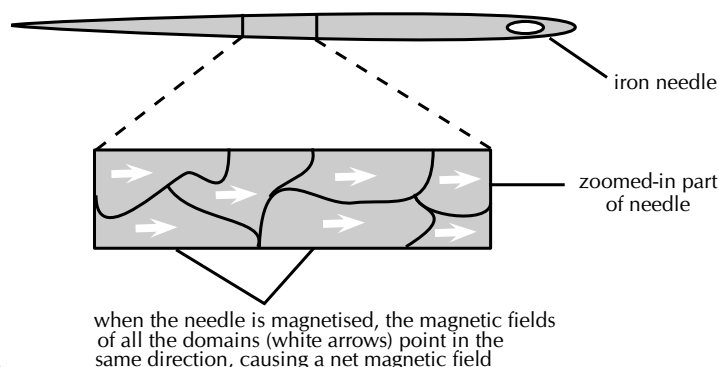
In some materials (e.g. iron), called **ferromagnetic** materials, there are regions called *domains*, where the electrons' magnetic fields line up with each other. All the atoms in each domain are grouped together so that the magnetic fields from their electrons point the same way. The picture shows a piece of an iron needle zoomed in to show the domains with the electric fields lined up inside them.

In permanent magnets, many domains are lined up, resulting in a *net magnetic field*. Objects made from ferromagnetic materials can be magnetised, for example by rubbing a magnet along the object in one direction. This causes the magnetic fields of most, or all, of the domains to line up in one direction. As a result the object as a whole will have a net magnetic field. It is *magnetic*. Once a ferromagnetic object has been magnetised, it can stay magnetic without another magnet being nearby (i.e. without being in another magnetic field). In the picture below, the needle has been magnetised because the magnetic fields in all the domains are pointing in the same direction.

A permanent magnet

Photograph by Harsh Patel

iron needle

zoomed-in part of needle

when the needle is magnetised, the magnetic fields of all the domains (white arrows) point in the same direction, causing a net magnetic field

Investigation: *Ferromagnetic materials and magnetisation*

1. Find 2 paper clips. Put the paper clips close together and observe what happens.
    a. What happens to the paper clips?
    b. Are the paper clips magnetic?
2. Now take a permanent bar magnet and rub it once along 1 of the paper clips. Remove the magnet and put the paper clip which was touched by the magnet close to the other paper clip and observe what happens. Does the untouched paper clip experience a force on it? If so, is the force attractive or repulsive?
3. Rub the same paper clip a few more times with the bar magnet, in the same direction as before. Put the paper clip close to the other one and observe what happens.
    a. Is there any difference to what happened in step 2?
    b. If there is a difference, what is the reason for it?
    c. Is the paper clip which was rubbed repeatedly by the magnet now magnetised?
    d. What is the difference between the two paper clips at the level of their atoms and electrons?
4. Now, find a *metal* knitting needle, or a metal ruler, or other metal object. Rub the bar magnet along the knitting needle a few times in the same direction. Now put the knitting needle close to the paper clips and observe what happens.
    a. Does the knitting needle attract the paper clips?

b. What does this tell you about the material of the knitting needle? Is it ferromagnetic?

5. Repeat this experiment with objects made from other materials. Which materials appear to be ferromagnetic and which are not? Put your answers in a table.

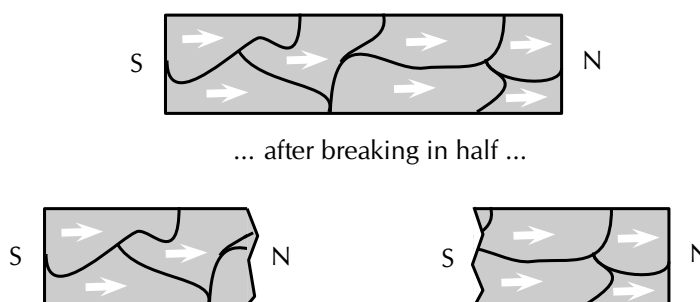
A ferromagnetic material is a substance that shows spontaneous magnetisation. Spontaneous means self-generated or to happen without external cause. This means that a ferromagnetic material has a magnetic field without any external factors being required.

Permanent magnets ESAEH

The poles of permanent magnets ESAEI

Because the domains in a permanent magnet all line up in a particular direction, the magnet has a pair of opposite poles, called **north** (usually shortened to **N**) and **south** (usually shortened to **S**). Even if the magnet is cut into tiny pieces, each piece will still have *both* a N and a S pole. These magnetic poles *always* occur in pairs. In nature, we never find a north magnetic pole or south magnetic pole on its own.

See video: VPflm at www.everythingscience.co.za

... after breaking in half ...

In nature, positive and negative electric charges can be found on their own, but you *never* find just a north magnetic pole or south magnetic pole on its own. On the very small scale, zooming in to the size of atoms, magnetic fields are caused by moving charges (i.e. the negatively charged electrons).

Magnetic attraction and repulsion *ESAEJ*

Like (identical) poles of magnets repel one another whilst unlike (opposite) poles attract. This means that two N poles or two S poles will push away from each other while a N pole and a S pole will be drawn towards each other.

Do you think the following magnets will repel or be attracted to each other?

We are given two magnets with the N pole of one approaching the N pole of the other. Since both poles are the same, the magnets will repel each other.

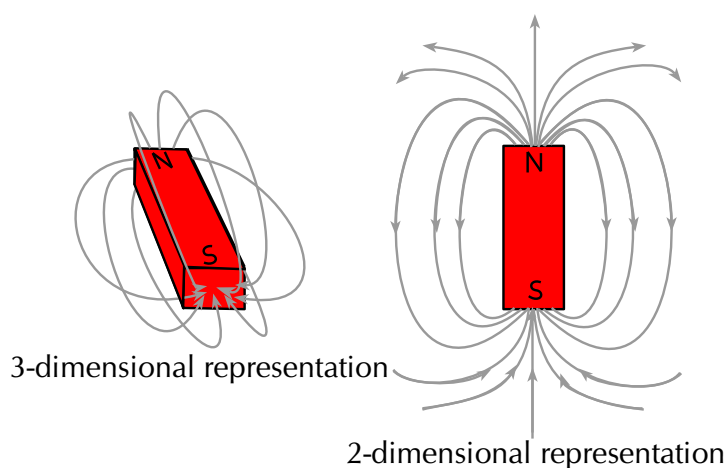
We are given two magnets with the N pole of one approaching the S pole of the other. Since both poles are the different, the magnets will be attracted to each other.

Representing magnetic fields *ESAEK*

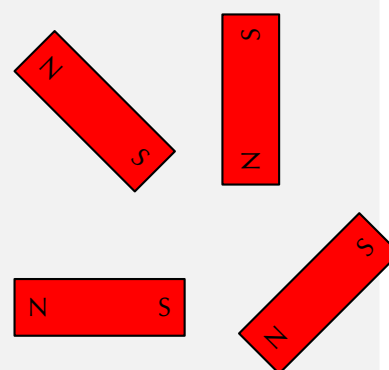
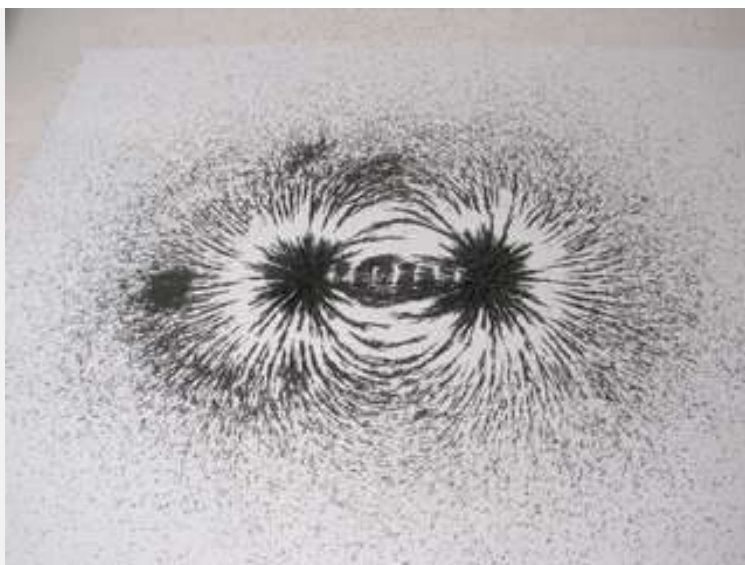
Magnetic fields can be *represented* using **magnetic field lines** starting at the North pole and ending at the South pole. Although the magnetic field of a permanent magnet is everywhere surrounding the magnet (in all three dimensions), we draw only some of the field lines to represent the field (usually only a two-dimensional cross-section is shown in drawings).

See video: VPfmc at www.everythingscience.co.za

Tip

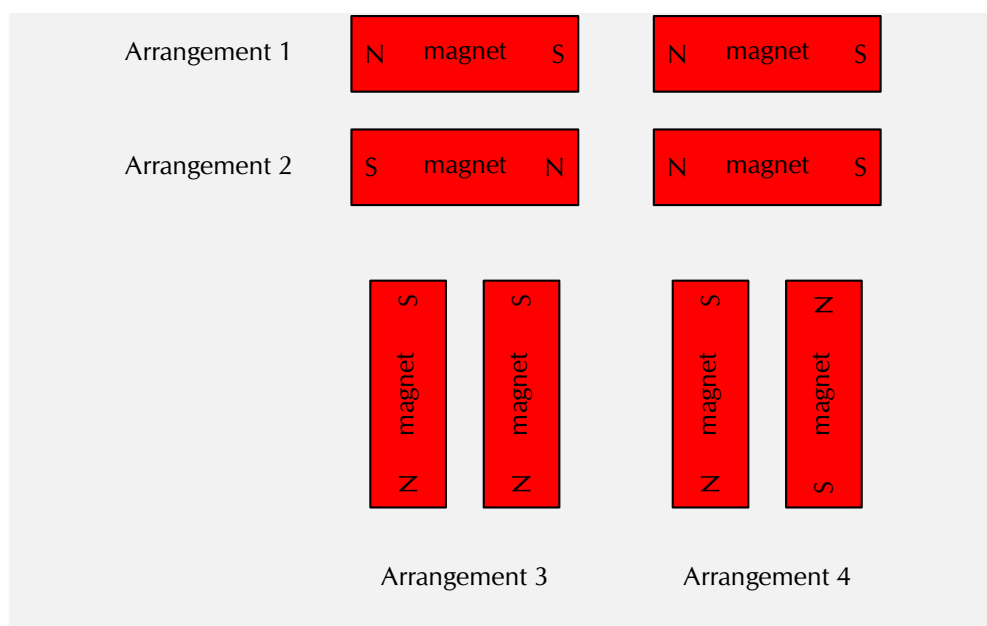
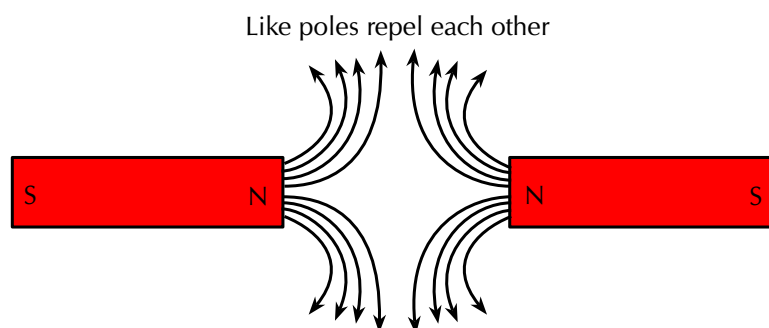
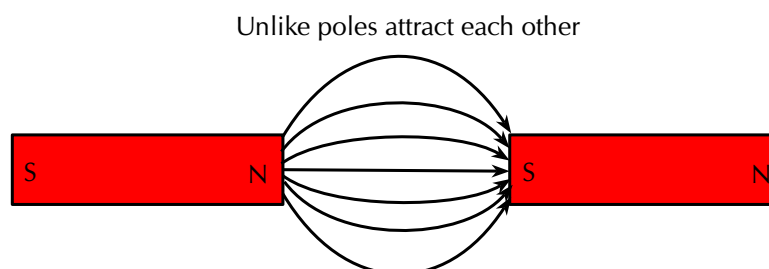
1. Field lines *never* cross.
2. Arrows drawn on the field lines indicate the direction of the field.
3. A magnetic field points from the north to the south pole of a magnet.

In areas where the magnetic field is strong, the field lines are closer together. Where the field is weaker, the field lines are drawn further apart. The number of field lines drawn crossing a given two-dimensional surface is referred to as the **magnetic flux**. The magnetic flux is used as a measure of the strength of the magnetic field through that surface.

Investigation: *Magnetic field around a bar magnet*

Take a bar magnet and place it under a non-magnetic, thin flat surface (this is to stop the paper bending). Place a sheet of white paper on the surface over the bar magnet and sprinkle some iron filings onto the paper. Give the paper a shake to evenly distribute the iron filings. In your workbook, draw the bar magnet and the pattern formed by the iron filings. Draw the pattern formed when you rotate the bar magnet to a different angle as shown alongside.

Iron filings revealing a magnetic field

Photograph by oskay on Flickr.com

As the investigation shows, one can map the magnetic field of a magnet by placing it underneath a piece of paper and sprinkling iron filings on top. The iron filings line themselves up parallel to the magnetic field.

Investigation: *Magnetic field around a pair of bar magnets*

Take two bar magnets and place them a short distance apart such that they are repelling each other. Place a sheet of white paper over the bar magnets and sprinkle some iron filings onto the paper. Give the paper a shake to evenly distribute the iron filings. In your workbook, draw both the bar magnets and the pattern formed by the iron filings. Repeat the procedure for two bar magnets attracting each other and draw what the pattern looks like for this situation. Make a note of the shape of the lines formed by the iron filings, as well as their size and their direction for both arrangements of the bar magnet. What does the pattern look like when you place both bar magnets side by side?

As already stated, opposite poles of a magnet attract each other and bringing them together causes their magnetic field lines to *converge* (come together). Like poles of a magnet repel each other and bringing them together causes their magnetic field lines to *diverge* (bend out from each other).

Ferromagnetism ESAEL

Ferromagnetism is a phenomenon shown by materials like iron, nickel or cobalt. These materials can form permanent magnets. They always magnetise so as to be attracted to a magnet, no matter which magnetic pole is brought toward the unmagnetised iron/nickel/cobalt.

Retentivity and magnetic materials [NOT IN CAPS] ESAEM

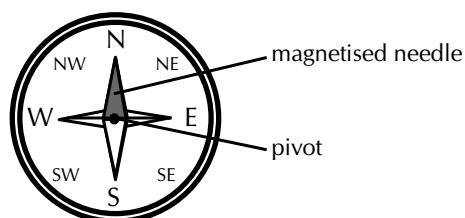
The ability of a ferromagnetic material to retain its magnetisation *after* an external field is removed is called its **retentivity**.

Paramagnetic materials are materials like aluminium or platinum, which become magnetised in an external magnetic field in a similar way to ferromagnetic materials. However, they lose their magnetism when the external magnetic field is removed.

Diamagnetism is shown by materials like copper or bismuth, which become magnetised in a magnetic field with a polarity *opposite* to the external magnetic field. Unlike iron, they are slightly repelled by a magnet.

The compass ESAEN

A **compass** is an instrument which is used to find the direction of a magnetic field. A compass consists of a small metal needle which is magnetised itself and which is free to turn in any direction. Therefore, when in the presence of a magnetic field, the needle is able to line up in the same direction as the field.

The direction of the compass arrow is the same as the direction of the magnetic field

FACT

Lodestone, a magnetised form of iron-oxide, was found to orientate itself in a north-south direction if left free to rotate by suspension on a string or on a float in water. Lodestone was therefore used as an early navigational compass.

Compasses are mainly used in navigation to find direction on the earth. This works because the Earth itself has a magnetic field which is similar to that of a bar magnet (see the picture below). The compass needle aligns with the Earth's magnetic field direction and points north-south. Once you know where north is, you can figure out any other direction. A photograph of a compass is shown on the right.

Some animals can detect magnetic fields, which helps them orientate themselves and navigate. Animals which can do this include pigeons, bees, Monarch butterflies, sea turtles and certain fish.

A compass

Photograph by Colin Zhu

The Earth's magnetic field

In the picture below, you can see a representation of the Earth's magnetic field which is very similar to the magnetic field of a giant bar magnet like the one on the right of the picture. The Earth has two **magnetic poles**, a north and a south pole just like a bar magnet.

In addition to the magnetic poles the Earth also has two **geographic poles**. The two geographic poles are the points on the Earth's surface where the line of the Earth's axis of rotation meets the surface. To visualise this you could take any round fruit (lemon, orange etc.) and stick a pencil through the middle so it comes out the other side. Turn the pencil, the pencil is the axis of rotation and the geographic poles are where the pencil enters and

exits the fruit. We call the geographic north pole **true north**.

The Earth's magnetic field has been measured very precisely and scientists have found that the magnetic poles do not correspond exactly to the geographic poles.

So the Earth has two north poles and two south poles: **geographic poles** and **magnetic poles**.

The Earth's magnetic field is thought to be caused by flowing liquid metals in the outer core of the planet which causes electric currents and a magnetic field. From the picture you can see that the direction of magnetic north and true north are not identical. The **geographic north pole** is about 11,5° away from the direction of the **magnetic north pole** (which is where a compass will point). However, the magnetic poles shift slightly all the time.

Another interesting thing to note is that if we think of the Earth as a big bar magnet, and we know that magnetic field lines always point *from north to south*, then the compass tells us that what we call the *magnetic north pole* is actually the *south pole* of the bar magnet!

FACT

The direction of the Earth's magnetic field flips direction about once every 200 000 years! You can picture this as a bar magnet whose north and south pole periodically switch sides. The reason for this is still not fully understood.

Phenomena related to the Earth's magnetic field

The importance of the magnetic field to life on Earth

The Earth's magnetic field is very important for humans and other animals on Earth because it protects us from being bombarded (hit) by high energy charged particles which are emitted by the Sun. The stream of charged particles (mainly positively charged protons and negatively charged electrons) coming from the sun is called the solar wind. When

these particles come close to the Earth, they are deflected by the Earth's magnetic field and cannot shower down to the surface where they can harm living organisms. Astronauts in space are at risk of being irradiated by the solar wind because they are outside the zones where the charged particles are trapped.

Visualisation of the magnetosphere

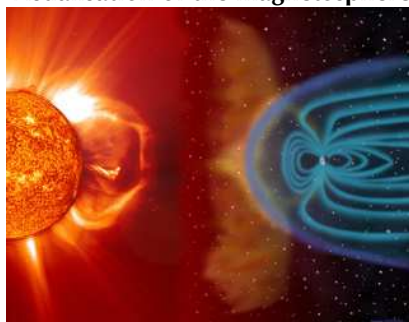



Photo by NASA Goddard Photo and Video on Flickr.com

The region above Earth's atmosphere in which charged particles are affected the Earth's magnetic field is called the magnetosphere. Relatively often, in addition to the usual solar wind, the Sun may eject a large bubble of material (protons and electrons) with its own magnetic field from its outer atmosphere. Sometimes these bubbles travel towards the Earth where their magnetic fields can join with Earth's magnetic field. When this happens a huge amount of energy is released into the Earth's magnetosphere, causing a geomagnetic storm. These storms cause rapid changes in the Earth's magnetosphere which in turn may affect electric and magnetic systems on the Earth such as power grids, cellphone networks, and other electronic systems.

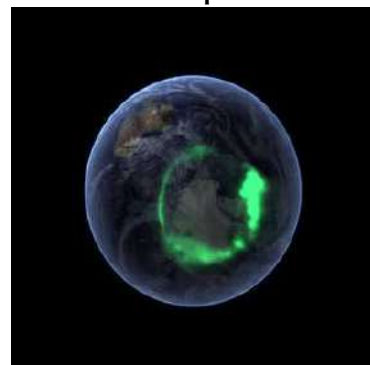
Aurorae (pronounced Or-roar-ee)

Another effect caused by the Earth's magnetic field is the spectacular Northern and Southern Lights, which are also called the Aurora Borealis and the Aurora Australis respectively.

When charged particles from the solar wind reach the Earth's magnetosphere, they spiral along the magnetic field lines towards the North and South poles. If they collide with particles in the Earth's atmosphere, they can cause red or green lights which stretch across a large part of the sky and which is called the aurora.

Aurora borealis photographed in Alaska

Photograph by Trodel on Flickr.com

Aurora australis photographed from space

Photograph by seishin17 on Flickr.com

As this only happens close to the North and South poles, we cannot see the aurorae from South Africa. However, people living in the high Northern latitudes in Canada, Sweden, and Finland, for example, often see the Northern lights.
See simulation: (Simulation: VPfkg at www.everythingscience.co.za)

Chapter 15 | Summary

See the summary presentation (Presentation: VPfjh at www.everythingscience.co.za)

- Magnets have two poles - North and South.
- Some substances can be easily magnetised.
- Like poles repel each other and unlike poles attract each other.
- The Earth also has a magnetic field.
- A compass can be used to find the magnetic north pole and help us find our direction.
- The Earth's magnetic field protects us from being bombarded by high energy charged particles which are emitted by the Sun.
- The Aurorae are an effect of the Earth's magnetic field.

Chapter 15 End of chapter exercises

1. Describe what is meant by the term *magnetic field*.
2. Use words and pictures to explain why permanent magnets have a magnetic field around them. Refer to *domains* in your explanation.
3. What is a magnet?
4. What happens to the poles of a magnet if it is cut into pieces?
5. What happens when like magnetic poles are brought close together?
6. What happens when unlike magnetic poles are brought close together?

7. Draw the shape of the magnetic field around a bar magnet.

8. Explain how a compass indicates the direction of a magnetic field.

9. Compare the magnetic field of the Earth to the magnetic field of a bar magnet using words and diagrams.

10. Explain the difference between the geographical north pole and the magnetic north pole of the Earth.

11. Give examples of phenomena that are affected by Earth's magnetic field.

12. Draw a diagram showing the magnetic field around the Earth.

More practice video solutions or help at www.everythingscience.co.za

(1.) 005z (2.) 0060 (3.) 0061 (4.) 0062 (5.) 0063 (6.) 0064
(7.) 0065 (8.) 0066 (9.) 0067 (10.) 0068 (11.) 0069 (12.) 006a

Electrostatics 16

Introduction and key concepts

Electrostatics is the study of electric charge which is at rest or static (not moving). In this chapter we will look at some of the basic principles of electrostatics as well as the principle of conservation of charge.

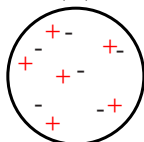
See introductory video: (Video: VPfmg at www.everythingscience.co.za)

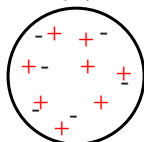
Two kinds of charge

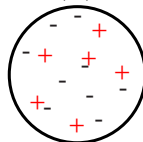
ESAER

All objects surrounding us (including people!) contain large amounts of electric charge. There are two types of electric charge: **positive** charge and **negative** charge. If the same amounts of negative and positive charge are found in an object, there is *no net charge* and the object is electrically **neutral**. If there is more of one type of charge than the other on the object then the object is said to be **electrically charged**. The picture below shows what the distribution of charges might look like for a neutral, positively charged and negatively charged object.

There are:

6 positive charges and
6 negative charges
6 + (-6) = 0

There is zero net charge:
The object is neutral

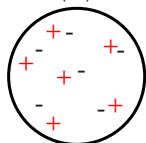
8 positive charges and
6 negative charges
8 + (-6) = 2

The net charge is +2
The object is positively charged

6 positive charges and
9 negative charges
6 + (-9) = -3

The net charge is -3
The object is negatively charged

Positive charge is carried by the protons in material and negative charge by electrons. The overall charge of an object is usually due to changes in the number of electrons. To make an object:

- **Positively charged**: electrons are removed making the object electron **deficient**.
- **Negatively charged**: electrons are added giving the object an **excess** of electrons.

So in practise what happens is that the number of positive charges (protons) remains the same and the number of electrons changes:

There are:

6 positive charges and 6 negative charges	**6** positive charges and 4 negative charges	**6** positive charges and 9 negative charges
6 + (-6) = 0	6 + (-4) = 2	6 + (-9) = -3
There is zero net charge: The object is neutral	The net charge is +2 The object is positively charged	The net charge is -3 The object is negatively charged

Tribo-electric charging

Tip

Charge, like energy, cannot be created or destroyed. We say that charge is **conserved**.

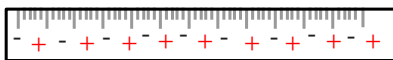
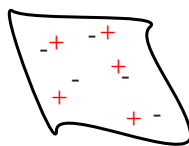
Objects may become charged in many ways, including by contact with or being rubbed by other objects. This means that they can gain or lose negative charge. For example, charging happens when you rub your feet against the carpet. When you then touch something metallic or another person, you feel a shock as the excess charge that you have collected is *discharged*.

When you rub your feet against the carpet, negative charge is transferred to you from the carpet. The carpet will then become positively charged by the *same amount*.

See video: VPfns at www.everythingscience.co.za

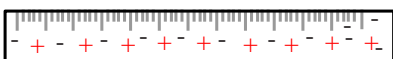
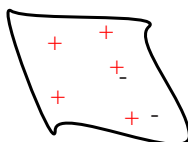
Another example is to take two *neutral* objects such as a plastic ruler and a cotton cloth (handkerchief). To begin, the two objects are neutral (i.e. have the same amounts of positive and negative charge).

Note: We represent the positive charge with a + and the negative charge with a -. This is just to **illustrate the balance and changes that occur, not the actual location** of the positive and negative charges. The charges are spread throughout the material and the real change happens by increasing or decreasing electrons on the surface of the materials.

BEFORE rubbing:

The ruler has 9 positive charges and 9 negative charges

The neutral cotton cloth has 5 positive charges and 5 negative charges

The total number of charges is:
$(9+5) = 14$ positive charges
$(9+5) = 14$ negative charges

Now, if the cotton cloth is used to rub the ruler, negative charge is transferred *from* the cloth *to* the ruler. The ruler is now *negatively* charged (i.e. has an excess of electrons) and the cloth is *positively* charged (i.e. is electron deficient). If you count up all the positive and negative charges at the beginning and the end, there are still the same amount, i.e. total charge has been *conserved*!

AFTER rubbing:

The ruler has 9 positive charges and 12 negative charges
It is now negatively charged.

The cotton cloth has 5 positive charges and 2 negative charges.
It is now positively charged.

The total number of charges is:
(9+5)=14 positive charges
(12+2)=14 negative charges

Charges have been transferred from the cloth to the ruler BUT total charge has been conserved!

Example 1: *Tribo-electric charging*

QUESTION

If you have a cotton cloth and a silk cloth and you rub them together, which becomes negatively charged?

SOLUTION

Step 1 : ***Analyse the information provided***

There are two materials provided and they will be rubbed together. This means we are dealing with the interaction between the materials. The question is related to the charge on the materials which we can assume were neutral to begin with. This means that we are dealing electrostatics and the interaction of materials leading to the materials

becoming charged is tribo-electric charging.

Step 2 : ***Extract material properties***

Locate the materials in the tribo-electric series. The key thing is to know which is more positive and more negative in the series. Silk falls above cotton in our table making it more positive in the series.

Step 3 : ***Apply principles***

We know that when two materials are rubbed the more negative one in the series gains electrons and the more positive one loses electrons. This means that silk will lose electrons and cotton will gain electrons.

A material becomes negatively charged when it has an excess of electrons, thus the cotton, which gains electrons, becomes negatively charged.

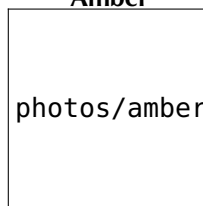
Note that in this example the numbers are made up to be easy to calculate. In the real world only a tiny fraction of the charges would move from one object to the other, but the total charge would still be conserved.

See simulation: (Simulation: VPgsz at www.everythingscience.co.za)

The process of materials becoming charged when they come into contact with other materials is known as tribo-electric charging. Materials can be arranged in a tribo-electric series according to the likelihood of them gaining or losing electrons.

If a material has equal numbers of positive and negative charges we describe it as being neutral (not favouring positive or negative overall charge).

If a neutral material loses electrons it becomes electron deficient and has an overall positive charge. If a neutral material gains electrons it has excess electrons and has an overall negative charge. For this reason we describe the ordering of materials in the tribo-electric series as more positive or more negative depending on whether they are more likely to lose or gain electrons.

Amber

Photograph by John Alan Elson on wikimedia

Aluminium

photos/Aluminium_wikimedia.jpg

Photograph on wikimedia

This tribo-electric series can allow us to determine whether one material is likely to become charged from another material.
Materials from the more positive end of the series are more likely to lose electrons than those from the more negative end. So when two materials are chosen and rubbed together the one that is more positive in the series will lose electrons and the one that is more negative in the series will gain electrons. For example, amber is more negative than wool and so if a piece of wool is rubbed against a piece of amber then the amber will become negatively charged.

Silicon

photos/Silicon_wikimedia.jpg

Photograph on wikimedia

Material	**Tribo-electric series**
Glass	Very positive
Human hair	
Nylon	
Wool	
Fur	
Lead	
Silk	
Aluminium	
Paper	
Cotton	
Steel	
Wood	
Amber	
Hard rubber	
Nickel, Copper	
Gold, Platinum	
Polyester	
Polyurethane	
Polypropylene	
Silicon	
Teflon	Very negative

Table 16.1: Tribo-electric series.

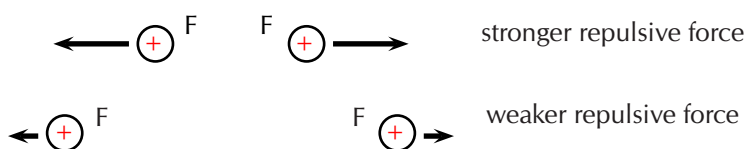
Force between charges

ESAET

The force exerted by non-moving (static) charges on each other is called the **electrostatic force.** The electrostatic force between:

- **like** charges is **repulsive**
- **opposite** (unlike) charges is **attractive**.

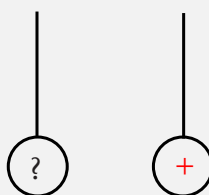
In other words, like charges repel each other while opposite charges attract each other.

The *closer* together the charges are, the *stronger* the electrostatic force between them.

FACT

The word "electron" comes from the Greek word for amber. The ancient Greeks observed that if you rubbed a piece of amber, you could use it to pick up bits of straw.

Example 2: *Application of electrostatic forces*

QUESTION

Two charged metal spheres hang from strings and are free to move as shown in the picture below. The right hand sphere is positively charged. The charge on the left hand sphere is unknown.

The left sphere is now brought close to the right sphere.

1. *If the left hand sphere swings towards the right hand sphere, what can you say about the charge on the left sphere and why?*
2. *If the left hand sphere swings away from the right hand sphere, what can you say about the charge on the left sphere and why?*

SOLUTION

Step 1 : ***Analyse the problem***

In the first case, we have a sphere with positive charge which is *attracting* the left charged sphere. We need to find the charge on the left sphere.

Step 2 : ***Identify the principles***

We are dealing with electrostatic forces between charged objects. Therefore, we know that *like* charges *repel* each other and *opposite* charges *attract* each other.

Step 3 : ***Apply the principles***

a. In the first case, the positively charged sphere is attracting the left sphere. Since an electrostatic force between unlike charges is attractive, the left sphere must be *negatively* charged.

b. In the second case, the positively charged sphere repels the left sphere. Like charges repel each other. Therefore, the left sphere must now also be *positively* charged.

Conservation of charge

ESAEU

In all of the examples we've looked at charge was not created or destroyed but it moved from one material to another.

DEFINITION: Principle of conservation of charge

The principle of conservation of charge states that the net charge of an isolated system remains constant during any physical process, e.g. two charge objects making contacting and separating.

Conductors and insulators ESAEV

Some materials allow electrons to move relatively freely through them (e.g. most metals, the human body). These materials are called **conductors**.

Tip

The effect of the shape on the charge distribution is the reason that we only consider identical conductors for the sharing of charge.

See video: VPfnt at www.everythingscience.co.za

Other materials do not allow the charge carriers, the electrons, to move through them (e.g. plastic, glass). The electrons are bound to the atoms in the material. These materials are called **non-conductors** or **insulators**.

If an excess of charge is placed on an insulator, it will stay where it is put and there will be a concentration of charge in that area of the object. However, if an excess of charge is placed on a conductor, the like charges will repel each other and spread out over the outside surface of the object. When two conductors are made to touch, the total charge on them is shared between the two. If the two conductors are identical, then each conductor will be left with half of the total net charge.

Arrangement of charge ESAEW

FACT

This collection of charge can actually allow charge to leak off the conductor if the point is sharp enough. It is for this reason that buildings often have a lightning rod on the roof to remove any charge the building has collected. This minimises the possibility of the building being struck by lightning. This "spreading out" of charge would not occur if we were to place the charge on an insulator since charge cannot move in insulators.

The electrostatic force determines the arrangement of charge on the surface of conductors. This is possible because charges can move inside a conductive material. When we place a charge on a spherical conductor the repulsive forces between the individual like charges cause them to spread uniformly over the surface of the sphere. However, for conductors with irregular shapes, there is a concentration of charge near the point or points of the object.

Notice in Figure 16.1 that we show a concentration of charge with more − or + signs, while we represent uniformly spread charges with uniformly spaced − or + signs.

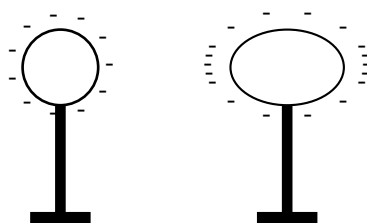



Figure 16.1: Charge on conductors

When two identical conducting spheres on insulating stands are allowed to touch they share the charge evenly between them. If the initial charge on the first sphere is Q_1 and the initial charge on the second sphere is Q_2, then the final charge on the two spheres after they have been brought into contact is:

$$Q = \frac{Q_1 + Q_2}{2}$$

Quantisation of charge

ESAEX

The basic unit of charge, called the elementary charge, *e*, is the amount of charge carried by one electron.

Unit of charge

ESAEY

The charge on a single electron is $q_e = 1,6 \times 10^{-19}$ C. All other charges in the universe consist of an integer multiple of this charge. This is known as charge quantisation.

$$\boxed{Q = nq_e}$$

Charge is measured in units called **coulombs (C)**. A coulomb of charge is a very large charge. In electrostatics we therefore often work with charge in micro-coulombs ($1\ \mu$C $= 1 \times 10^{-6}$ C) and nanocoulombs (1 nC $= 1 \times 10^{-9}$ C).

FACT

In 1909 Robert Millikan and Harvey Fletcher measured the charge on an electron. This experiment is now known as Millikan's oil drop experiment. Millikan and Fletcher sprayed oil droplets into the space between two charged plates and used what they knew about forces and in particular the electric force to determine the charge on an electron.

Example 3: Charge quantisation

QUESTION

An object has an excess charge of $-1,92 \times 10^{-17}$ C. How many excess electrons

does it have?

SOLUTION

Step 1 : ***Analyse the problem and identify the principles***

We are asked to determine a number of electrons based on a total charge. We know that charge is quantised and that electrons carry the base unit of charge which is $-1,6 \times 10^{-19}$ C.

Step 2 : ***Apply the principle***

As each electron carries the same charge the total charge must be made up of a certain number of electrons. To determine how many electrons we divide the total charge by the charge on a single electron:

$$\begin{aligned} N &= \frac{-1,92 \times 10^{-17}}{-1,6 \times 10^{-19}} \\ &= 120 \text{ electrons} \end{aligned}$$

Example 4: *Conducting spheres and movement of charge*

QUESTION

I have 2 charged metal conducting spheres on insulating stands which are identical except for having different charge. Sphere A has a charge of -5 nC and sphere B has a charge of -3 nC. I then bring the spheres together so that they touch each other. Afterwards I move the two spheres apart so that they are no longer touching.

1*. What happens to the charge on the two spheres?*

2*. What is the final charge on each sphere?*

SOLUTION

Step 1 : ***Analyse the question***

We have two identical negatively charged conducting spheres which are brought together to touch each other and then taken apart again.

We need to explain what happens to the charge on each sphere and what the final charge on each sphere is after they are moved apart.

Step 2 : ***Identify the principles involved***

We know that the charge carriers in conductors are free to move around and that charge on a conductor spreads itself out on the surface of the conductor.

Step 3 : ***Apply the principles***

a. When the two conducting spheres are brought together to touch, it is as though they become one single big conductor and the total charge of the two spheres spreads out across the whole surface of the touching spheres. When the spheres are moved apart again, each one is left with half of the total original charge.

b. Before the spheres touch, the total charge is: -5 nC + (-3) nC = -8 nC. When they touch they share out the -8 nC across their whole surface. When they are removed from each other, each is left with half of the original charge:

$$\frac{-8 \text{ nC}}{2} = -4 \text{ nC}$$

on each sphere.

Example 5: *Identical spheres sharing charge I*

QUESTION

Two identical, insulated spheres have different charges. Sphere 1 has a charge of -96×10^{-18} C. Sphere 2 has 60 excess electrons. If the two spheres are brought into contact and then separated, what charge will each have?

SOLUTION

Step 1 : ***Analyse the question***

We need to determine what will happen to the charge when the spheres touch. They are insulators so we know they will NOT allow charge to

move freely. When they touch nothing will happen.

Example 6: *Identical spheres sharing charge II*

QUESTION

Two identical, metal spheres on insulating stands have different charges. Sphere 1 has a charge of $-9,6 \times 10^{-18}$ C. Sphere 2 has 60 excess protons. If the two spheres are brought into contact and then separated, what charge will each have? How many electrons or protons does this correspond to?

SOLUTION

Step 1 : ***Analyse the question***

We need to determine what will happen to the charge when the spheres touch. They are metal spheres so we know they will be conductors. This means that the charge is able to move so when they touch it is possible for the charge on each sphere to change. We know that charge will redistribute evenly across the two spheres because of the forces between the charges. We need to know the charge on each sphere, we have been given one.

Step 2 : ***Identify the principles involved***

This problem is similar to the earlier worked example. This time we have to determine the total charge given a certain number of protons. We know that charge is quantised and that protons carry the base unit of charge and are positive so it is $+1,6 \times 10^{-19}$ C.

Step 3 : ***Apply the principles***

The total charge will therefore be:

$$\begin{aligned} Q_2 &= 60 \times 1,6 \times 10^{-19} \text{ C} \\ &= 9,6 \times 10^{-18} \text{ C} \end{aligned}$$

As the spheres are identical in material, size and shape the charge will redistribute across the two spheres so that it is shared evenly. Each

sphere will have half of the total charge:

$$\begin{aligned} Q &= \frac{Q_1 + Q_2}{2} \\ &= \frac{9,6 \times 10^{-18} + \left(-9,6 \times 10^{-18}\right)}{2} \\ &= 0\,\text{C} \end{aligned}$$

So each sphere is now neutral.

No net charge means that there is no excess of electrons or protons.

Example 7: *Conservation of charge*

QUESTION

Two identical, metal spheres have different charges. Sphere 1 has a charge of $-9,6 \times 10^{-18}$ C. Sphere 2 has 30 excess electrons. If the two spheres are brought into contact and then separated, what charge will each have? How many electrons does this correspond to?

SOLUTION

Step 1 : ***Analyse the problem***

We need to determine what will happen to the charge when the spheres touch. They are metal spheres so we know they will be conductors. This means that the charge is able to move so when they touch it is possible for the charge on each sphere to change. We know that charge will redistribute evenly across the two spheres because of the forces between the charges. We need to know the charge on each sphere, we have been given one.

Step 2 : ***Identify the principles***

This problem is similar to the earlier worked example. This time we have to determine the total charge given a certain number of electrons. We know that charge is quantised and that electrons carry the base unit of charge which is $-1,6 \times 10^{-19}$ C. The total charge will therefore be:

$$\begin{aligned} Q_2 &= 30 \times -1,6 \times 10^{-19}\,\text{C} \\ &= 4,8 \times 10^{-18}\,\text{C} \end{aligned}$$

Step 3 : ***Apply the principles: redistributing charge***

As the spheres are identical in material, size and shape the charge will redistribute across the two spheres so that it is shared evenly. Each sphere will have half of the total charge:

$$\begin{aligned} Q &= \frac{Q_1 + Q_2}{2} \\ &= \frac{-9.6 \times 10^{-18} + \left(-4,8 \times 10^{-18}\right)}{2} \\ &= 7,2 \times 10^{-18} \text{ C} \end{aligned}$$

So each sphere now has:

$$7,2 \times 10^{-18} \text{ C}$$

of charge.

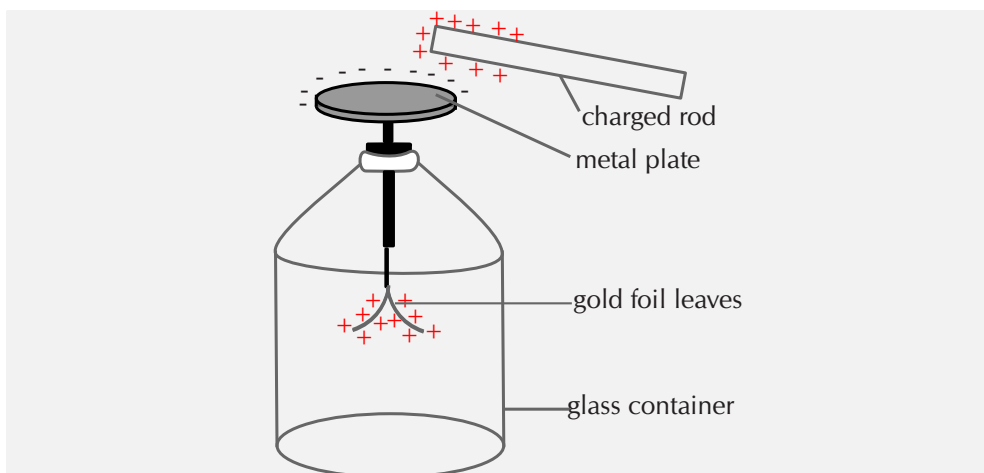
We know that charge is quantised and that electrons carry the base unit of charge which is $-1,6 \times 10^{-19}$ C.

Step 4 : ***Apply the principles: charge quantisation***

As each electron carries the same charge the total charge must be made up of a certain number of electrons. To determine how many electrons we divide the total charge by the charge on a single electron:

$$\begin{aligned} N &= \frac{-7,2 \times 10^{-18}}{-1,6 \times 10^{-19}} \\ &= 45 \text{ electrons} \end{aligned}$$

Investigation: *The electroscope*

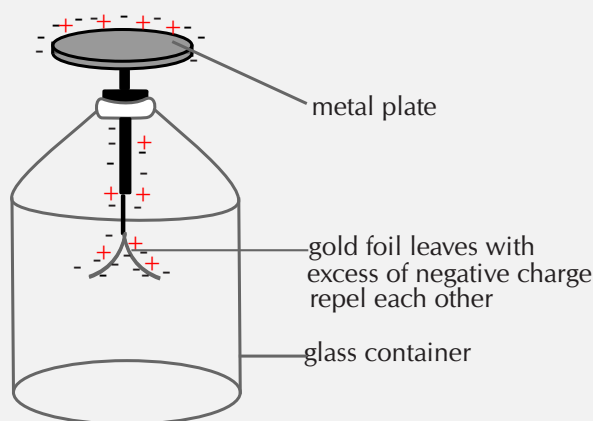
The electroscope is a very sensitive instrument which can be used to detect electric charge. A diagram of a gold leaf electroscope is shown the figure below. The electroscope consists of a glass container with a metal rod inside which has 2 thin pieces of gold foil attached. The other end of the metal rod has a metal plate attached to it outside the glass container.

The electroscope detects charge in the following way: A charged object, like the positively charged rod in the picture, is brought close to (but not touching) the neutral metal plate of the electroscope. This causes negative charge in the gold foil, metal rod, and metal plate, to be attracted to the positive rod. Because the metal (gold is a metal too!) is a conductor, the charge can move freely from the foil up the metal rod and onto the metal plate. There is now more negative charge on the plate and more positive charge on the gold foil leaves. This is called *inducing* a charge on the metal plate. It is important to remember that the electroscope is still neutral (the total positive and negative charges are the same), the charges have just been induced to *move* to different parts of the instrument! The induced positive charge on the gold leaves forces them apart since like charges repel! This is how we can tell that the rod is charged. If the rod is now moved away from the metal plate, the charge in the electroscope will spread itself out evenly again and the leaves will fall down because there will no longer be an induced charge on them.

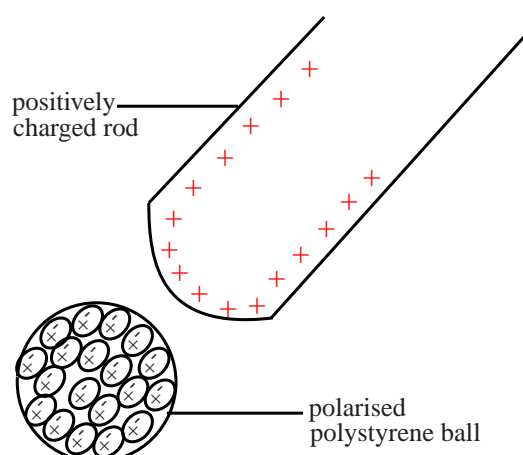
Grounding

If you were to bring the charged rod close to the uncharged electroscope, and then you touched the metal plate with your finger at the same time, this would cause charge to flow up from the ground (the earth), through your body onto the metal plate. Connecting to the earth so charge flows is called **grounding**. The charge flowing onto the plate is opposite to the charge on the rod, since it is attracted to the charge on the rod. Therefore, for our picture, the charge flowing onto the plate would be negative. Now that charge has been added to the electroscope, it is no longer neutral, but has an excess of negative charge. Now if we move the rod away, the leaves will remain apart because they have an excess of negative charge and they repel each other. If we ground

the electroscope again (this time without the charged rod nearby), the excess charge will flow back into the earth, leaving it neutral.

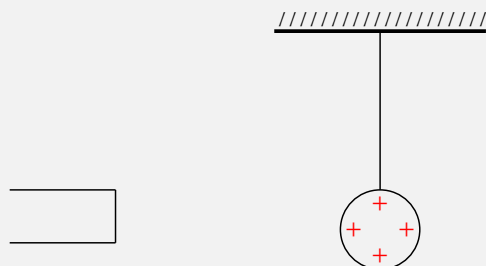
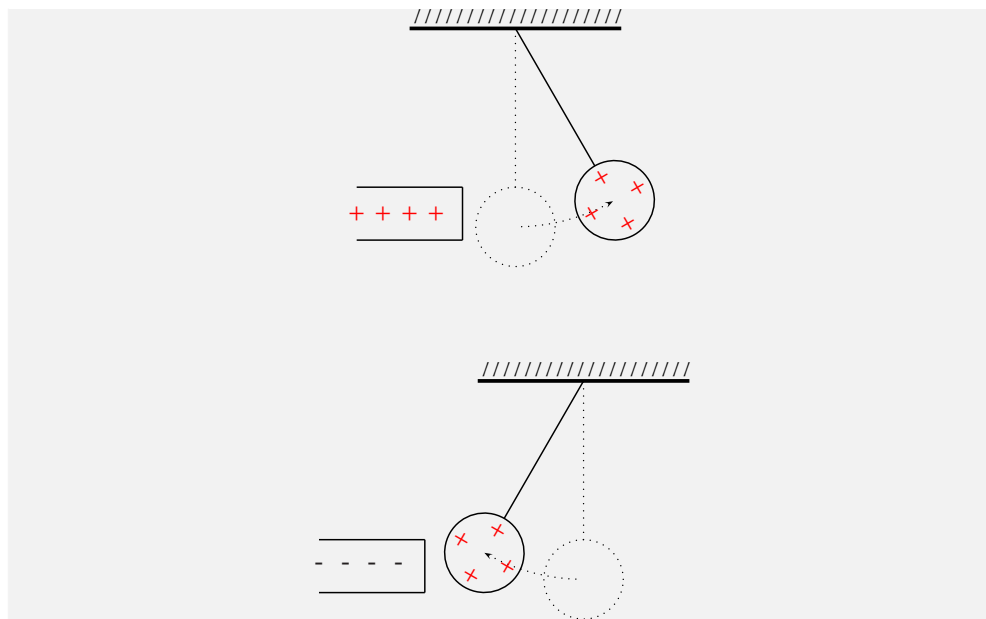
Polarisation

ESAEZ

Unlike conductors, the electrons in insulators (non-conductors) are bound to the atoms of the insulator and cannot move around freely through the material. However, a charged object can still exert a force on a neutral insulator due to a phenomenon called **polarisation**.

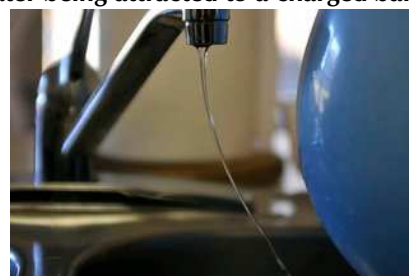
If a positively charged rod is brought close to a neutral insulator such as polystyrene, it can attract the bound electrons to move round to the side of the atoms which is closest to the rod and cause the positive nuclei to move slightly to the opposite side of the atoms. This process is called *polarisation*. Although it is a very small (microscopic) effect, if there are many atoms and the polarised object is light (e.g. a small polystyrene ball), it can add up to enough force to cause the object to be attracted onto the charged rod. Remember, that the polystyrene is *only* polarised, *not charged*. The polystyrene ball is still neutral since no charge was added or removed from it. The picture shows a not-to-scale view of the polarised atoms in the polystyrene ball:

Some materials are made up of molecules which are already polarised. These are molecules which have a more positive and a more negative side but are still neutral overall. Just as a polarised polystyrene ball can be attracted to a charged rod, these materials are also affected if brought close to a charged object.

Investigation: *Electrostatic force*

You can easily test that like charges repel and unlike charges attract each other by doing a very simple experiment.

Take a glass ball and rub it with a piece of silk, then hang it from its middle with a piece string so that it is free to move. If you then bring another glass rod which you have also charged in the same way next to it, you will see the ball on the string move *away* from the rod in your hand i.e. it is **repelled**. If, however, you take a plastic rod, rub it with a piece of fur and then bring it close to the ball on the string, you will see the rod on the string move *towards* the rod in your hand i.e. it is **attracted**.

This happens because when you rub the glass with silk, tiny amounts of negative charge are transferred from the glass onto the silk, which causes the glass to have less negative charge than positive charge, making it **positively charged**. When you rub the plastic rod with the fur, you transfer tiny amounts of negative charge onto the rod and so it has more negative charge than positive charge on it, making it **negatively charged**.

Water is an example of a substance which is made of polarised molecules. If a positively charged rod, comb or balloon is brought close to a stream of water, the molecules can rotate so that the negative sides all line up towards the rod. The stream of water will then be attracted to the positively charge object since opposite charges attract.

Water being attracted to a charged balloon

Photograph by NASA

Chapter 16 | Summary

See the summary presentation (Presentation: VPfqd at www.everythingscience.co.za)

- There are two kinds of charge: positive and negative.
- Positive charge is carried by protons in the nucleus.
- Negative charge is carried by electrons.
- Objects can be **positively** charged, **negatively** charged or **neutral**.
- Objects that are neutral have equal numbers of positive and negative charge.
- Unlike charges are attracted to each other and like charges are repelled from each other.
- Charge is neither created nor destroyed, it can only be transferred.
- Charge is measured in coulombs (C).
- Charge is quantised in units of the charge of an electron 1.6×10^{-19} C, $Q = nq_e$.
- Conductors allow charge to move through them easily.
- Insulators do not allow charge to move through them easily.
- Identical, conducting spheres in contact share their charge according to:

$$Q = \frac{Q_1 + Q_2}{2}$$

Physical Quantities		
Quantity	**Unit name**	**Unit symbol**
Charge (Q)	coulomb	C
Charge on the electron (q_e)	coulomb	C

Table 16.2: Units used in **electrostatics**

Chapter 16 End of chapter exercises

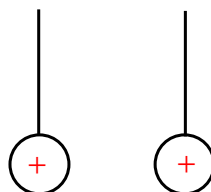
1. What are the two types of charge called?

2. Provide evidence for the existence of two types of charge.

3. Fill in the blanks: The electrostatic force between like charges is ________ while the electrostatic force between opposite charges is ________ .

4. I have two positively charged metal balls placed 2 m apart.
   a. Is the electrostatic force between the balls attractive or repulsive?

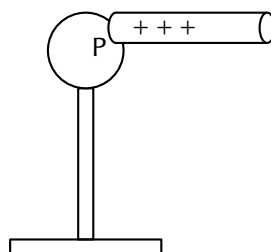
b. If I now move the balls so that they are 1 m apart, what happens to the strength of the electrostatic force between them?

5. I have 2 charged spheres each hanging from string as shown in the picture below.

Choose the correct answer from the options below: The spheres will

a. swing towards each other due to the attractive electrostatic force between them.
b. swing away from each other due to the attractive electrostatic force between them.
c. swing towards each other due to the repulsive electrostatic force between them.
d. swing away from each other due to the repulsive electrostatic force between them.

6. Describe how objects (insulators) can be charged by contact or rubbing.

7. You are given a perspex ruler and a piece of cloth.
   a. How would you charge the perspex ruler?
   b. Explain how the ruler becomes charged in terms of charge.
   c. How does the charged ruler attract small pieces of paper?

8. (IEB 2005/11 HG) An uncharged hollow metal sphere is placed on an insulating stand. A positively charged rod is brought up to touch the hollow metal sphere at P as shown in the diagram below. It is then moved away from the sphere.

Where is the excess charge distributed on the sphere after the rod has been removed?

a. It is still located at point P where the rod touched the sphere.
b. It is evenly distributed over the outer surface of the hollow sphere.
c. It is evenly distributed over the outer and inner surfaces of the hollow sphere.

d. No charge remains on the hollow sphere.

9. What is the process called where molecules in an uncharged object are caused to align in a particular direction due to an external charge?

10. Explain how an uncharged object can be attracted to a charged object. You should use diagrams to illustrate your answer.

11. Explain how a stream of water can be attracted to a charged rod.

12. An object has an excess charge of $-8,6 \times 10^{-18}$ C. How many excess electrons does it have?

13. An object has an excess of 235 electrons. What is the charge on the object?

14. An object has an excess of 235 protons. What is the charge on the object?

15. Two identical, metal spheres have different charges. Sphere 1 has a charge of $-4,8 \times 10^{-18}$ C. Sphere 2 has 60 excess electrons. If the two spheres are brought into contact and then separated, what charge will each have? How many electrons does this correspond to?

16. Two identical, insulated spheres have different charges. Sphere 1 has a charge of $-96 \times 10^{-18}\,C$. Sphere 2 has 60 excess electrons. If the two spheres are brought into contact and then separated, what charge will each have?

17. Two identical, metal spheres have different charges. Sphere 1 has a charge of $-4,8 \times 10^{-18}$ C. Sphere 2 has 30 excess protons. If the two spheres are brought into contact and then separated, what charge will each have? How many electrons or protons does this correspond to?

More practice video solutions or help at www.everythingscience.co.za

(1.) 006b (2.) 006c (3.) 006d (4.) 006e (5.) 006f (6.) 006g
(7.) 006h (8.) 006i (9.) 006j (10.) 006k (11.) 006m (12.) 006n
(13.) 006p (14.) 006q (15.) 006r (16.) 006s (17.) 006t

Electric circuits 17

Potential difference and emf

ESAFA

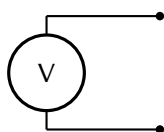
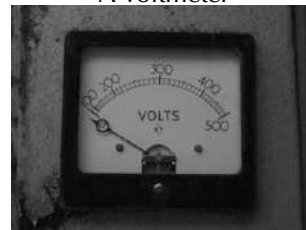
When a circuit is connected and complete, charge can move through the circuit. Charge will not move unless there is a reason, a force to drive it round the circuit. Think of it as though charge is at rest and something has to push it along. This means that work needs to be done to make charge move. A force acts on the charges, doing work, to make them move. The force is provided by the battery in the circuit.

A battery has the potential to drive charge round a closed circuit, the battery has potential energy that can be converted into electrical energy by doing work on the charge in the circuit to make it move.
See introductory video: (Video: VPfqj at www.everythingscience.co.za)

> *DEFINITION: Potential Difference*
>
> Potential difference is the work done per unit charge, $\frac{W}{q}$. The units of potential difference are the volt (V) which is defined as one joule per coulomb.
> Quantity: Potential difference (V) Unit name: volt Unit symbol: V

Voltmeter

ESAFB

A voltmeter is an instrument for measuring the potential difference between two points in an electric circuit.
The symbol for a voltmeter is:

A voltmeter

Photography by windy_ on Flickr.com

EMF

ESAFC

When you measure the potential difference across (or between) the terminals of a battery that is **not in a complete circuit** you are measuring the emf of the battery. This is the maximum amount of work per coulomb of charge the battery can do to drive charge from one terminal, through the circuit, to the other terminal.

FACT

The volt is named after the Italian physicist Alessandro Volta (1745–1827).

Electrical potential difference is also called voltage.

When you measure the potential difference across (or between) the terminals of a battery that is **in a complete circuit** you are measuring the terminal potential difference of the battery. Although this is measured in volts it is not identical to the emf. The difference will be the work done to drive charge through the battery.

Batteries

Photography on Flickr.com

One lead of the voltmeter is connected to one end of the battery and the other lead is connected to the opposite end. The voltmeter may also be used to measure the voltage across a resistor or any other component of a circuit but must be connected in parallel.

Current

Flow of charge

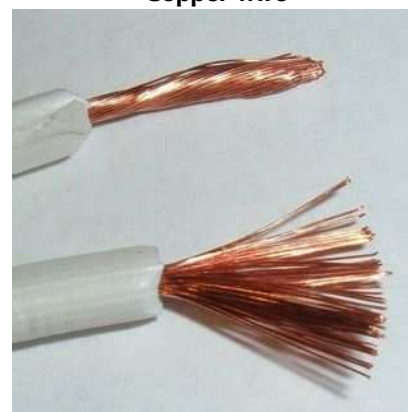
ESAFE

When we talk about current we talk about how much charge moves past a fixed point in circuit in one second. Think of charges being pushed around the circuit by the battery, there are charges in the wires but unless there is a battery they won't move.

See video: VPfva at www.everythingscience.co.za

When one charge moves the charges next to it also move. They keep their spacing as if you had a tube of marbles like in this picture or looked at a train and its carriages.

If you push one marble into the tube one must come out the other side, if a train locomotive moves all the carriages move immediately because they are connected. This is similar to charges in the wires of a circuit.

The idea is that if a battery started to drive charge in a circuit all the charges start moving instantaneously.

Photography on Flickr.com

> ### DEFINITION: Current
>
> Current is the rate at which charges moves past a fixed point in a circuit. The units of current are the ampere (A) which is defined as one coulomb per second.
>
> Quantity: Current (I) Unit name: ampere Unit symbol: A

FACT

Benjamin Franklin made a guess about the direction of charge flow when rubbing smooth wax with rough wool. He thought that the charges flowed from the wax to the wool (i.e. from positive to negative) which was opposite to the real direction. Due to this, electrons are said to have a *negative* charge and so objects which Ben Franklin called "negative" (meaning a shortage of charge) really have an excess of electrons. By the time the true direction of electron flow was discovered, the convention of "positive" and "negative" had already been so well accepted in the scientific world that no effort was made to change it.

Plasma ball

Photography by ahisgett on Flickr.com

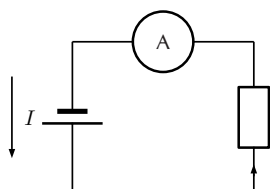
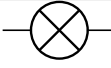
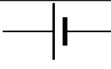
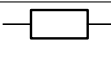
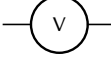
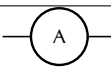
We use the symbol I to show current and it is measured in amperes (A). One ampere is one coulomb of charge moving in one second ($\text{C} \cdot \text{s}^{-1}$).

$$\boxed{I = \frac{Q}{\Delta t}}$$

When current flows in a circuit we show this on a diagram by adding arrows. The arrows show the direction of flow in a circuit. By convention we say that charge flows from the positive terminal on a battery to the negative terminal.

If the voltage is high enough a current can be driven through almost anything. In the plasma ball example on the left, a voltage is created that is high enough to get charge to flow through the gas in the ball. The voltage is very high but the resulting current is very low. This makes it safe to touch.

Ammeter

An ammeter is an instrument used to measure the rate of flow of electric current in a circuit. Since one is interested in measuring the current flowing *through* a circuit component, the ammeter must be connected in *series* with the measured circuit component.

Ammeter

Activity:	*Constructing circuits*

Construct circuits to measure the emf and the terminal potential difference for a battery. Some common elements (components) which can be found in electrical circuits include light bulbs, batteries, connecting leads, switches, resistors, voltmeters and ammeters. You have learnt about many of these already. Below is a table with

the items and their symbols:

Component	Symbol	Usage
light bulb		glows when charge moves through it
battery		provides energy for charge to move
switch		allows a circuit to be open or closed
resistor	OR	resists the flow of charge
voltmeter	V	measures potential difference
ammeter	A	measures current in a circuit
connecting lead		connects circuit elements together

Experiment with different combinations of components in the circuits.

Tip

A battery **does not** produce the same amount of current no matter what is connected to it. While the voltage produced by a battery is constant, the amount of current supplied depends on what is in the circuit.

The table below summarises the use of each measuring instrument that we discussed and the way it should be connected to a circuit component.

Instrument	Measured Quantity	Proper Connection
Voltmeter	Voltage	In Parallel
Ammeter	Current	In Series

Activity: *Using meters*

If possible, connect meters in circuits to get used to the use of meters to measure electrical quantities. If the meters have more than one scale, always connect to the **largest scale** first so that the meter will not be damaged by having to measure values that exceed its limits.

Example 1: *Calculating current I*

QUESTION

An amount of charge equal to 45 C moves past a point in a circuit in 1 second, what is the current in the circuit?

SOLUTION

Step 1 : ***Analyse the question***

We are given an amount of charge and a time and asked to calculate the current. We know that current is the rate at which charge moves past a fixed point in a circuit so we have all the information we need. We have quantities in the correct units already.

Step 2 : ***Apply the principles***

We know that:

$$\begin{aligned} I &= \frac{Q}{\Delta t} \\ I &= \frac{45\ \mathrm{C}}{1\ \mathrm{s}} \\ I &= 45\ \mathrm{C} \cdot \mathrm{s}^{-1} \\ I &= 45\ \mathrm{A} \end{aligned}$$

Step 3 : ***Quote the final result***

The current is 45 A.

Example 2: *Calculating current II*

QUESTION

An amount of charge equal to 53 C moves past a fixed point in a circuit in 2

seconds, what is the current in the circuit?

SOLUTION

Step 1 : ***Analyse the question***

We are given an amount of charge and a time and asked to calculate the current. We know that current is the rate at which charge moves past a fixed point in a circuit so we have all the information we need. We have quantities in the correct units already.

Step 2 : ***Apply the principles***

We know that:

$$\begin{aligned} I &= \frac{Q}{\Delta t} \\ I &= \frac{53 \text{ C}}{2 \text{ s}} \\ I &= 26,5 \text{ C} \cdot \text{s}^{-1} \\ I &= 26,5 \text{ A} \end{aligned}$$

Step 3 : ***Quote the final result***

The current is 26,5 A.

Example 3: *Calculating current III*

QUESTION

95 electrons move past a fixed point in a circuit in one tenth of a second, what is the current in the circuit?

SOLUTION

Step 1 : ***Analyse the question***

We are given a number of charged particles that move past a fixed point and the time that it takes. We know that current is the rate at which charge moves past a fixed point in a circuit so we have to determine the charge. In the last chapter we learnt that the charge carried by an

electron is $1,6 \times 10^{-19}$ C.

Step 2 : ***Apply the principles: determine the charge***

We know that each electron carries a charge of $1,6 \times 10^{-19}$ C, therefore the total charge is:

$$\begin{aligned} Q &= 95 \times 1,6 \times 10^{-19} \text{ C} \\ &= 1,52 \times 10^{-17} \text{ C} \end{aligned}$$

Step 3 : ***Apply the principles: determine the charge***

We know that:

$$\begin{aligned} I &= \frac{Q}{\Delta t} \\ I &= \frac{1,52 \times 10^{-17} \text{ C}}{\frac{1}{10} \text{ s}} \\ I &= \frac{1,52 \times 10^{-17} \text{ C}}{1} \times \frac{1}{\frac{1}{10} \text{ s}} \\ I &= \frac{1,52 \times 10^{-17} \text{ C}}{1} \times \frac{10}{1 \text{ s}} \\ I &= 1,52 \times 10^{-16} \text{ C} \cdot \text{s}^{-1} \\ I &= 1,52 \times 10^{-16} \text{ A} \end{aligned}$$

Step 4 : ***Quote the final result***

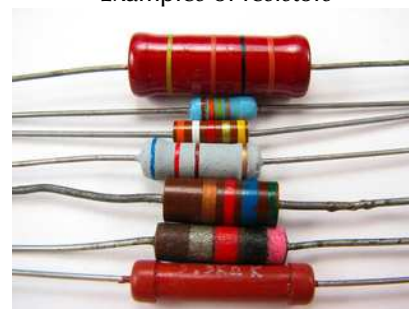
The current is $1,52 \times 10^{-16}$ A.

Resistance

Resistance is a measure of "how hard" it is to "push" electricity through a circuit element. Resistance can also apply to an entire circuit. See video: VPfvk at www.everythingscience.co.za

What causes resistance? ESAFH

On a microscopic level, electrons moving through the conductor collide (or interact) with the particles of which the conductor (metal) is made. When they collide, they transfer kinetic energy. The electrons therefore lose kinetic energy and slow down. This leads to resistance. The transferred energy causes the resistor to heat up. You can feel this directly if you touch a cellphone charger when you are charging a cell phone - the charger gets warm because its circuits have some resistors in them!

Examples of resistors

Photograph by oskay on Flickr.com

DEFINITION: Resistance

Resistance slows down the flow of charge in a circuit. The unit of resistance is the ohm (Ω) which is defined as a volt per ampere of current.
Quantity: Resistance R Unit: ohm Unit symbol: ω

FACT

Fluorescent lightbulbs do not use thin wires; they use the fact that certain gases glow when a current flows through them. They are much more efficient (much less resistance) than lightbulbs.

$$1 \text{ ohm} = 1 \frac{\text{volt}}{\text{ampere}}$$

Light bulb filament

Photograph by clagnut on Flickr.com

All conductors have some resistance. For example, a piece of wire has less resistance than a light bulb, but both have resistance.

A lightbulb is a very thin wire surrounded by a glass housing The high resistance of the small wire (filament) in a lightbulb causes the electrons to transfer a lot of their kinetic energy in the form of heat. The heat energy is enough to cause the filament to glow white-hot which produces light.

The wires connecting the lamp to the cell or battery hardly even get warm while conducting the same amount of current. This is because of their much lower resistance due to their larger cross-section (they are thicker).

An important effect of a resistor is that it *converts* electrical energy into other forms of **heat** energy. **Light** energy is a by-product of the heat that is produced.

FACT

There is a special type of conductor, called a **superconductor** that has no resistance, but the materials that make up all known superconductors only start superconducting at very low temperatures. The "highest" temperature superconductor is mercury barium calcium copper oxide ($HgBa_2Ca_2Cu_3O_x$) which is superconducting for temperatures of -140^o C and colder.

Physical attributes affecting resistance [NOT IN CAPS]

The physical attributes of a resistor affect its total resistance.

- **Length**: if a resistor is increased in length its resistance will increase. Typically if you increase the length of a resistor by a certain factor you will increase the resistance by the same factor.
- **Width and height or cross-sectional area**: if a resistor provides a larger pathway by being made wider or broader then more current can flow through it. If the total surface area through which current flows (cross-sectional area) is increased by a factor the resistance typically decreases by the same factor.

Extension: For a single resistor this can be summarised as

$$R \propto \frac{L}{A},$$

where L is the length and A is the cross-sectional area.

Why do batteries go flat?

A battery stores chemical potential energy. When it is connected in a circuit, a chemical reaction takes place inside the battery which converts chemical potential energy to electrical energy which powers the electrons to move through the circuit. All the circuit elements (such as the conducting leads, resistors and lightbulbs) have some resistance to the flow of charge and convert the electrical energy to heat and, in the case of the lightbulb, light. Since energy is always conserved, the battery goes flat when all its chemical potential energy has been converted into other forms of energy.

Resistors in electric circuits

It is important to understand what effect adding resistors to a circuit has on the *total* resistance of a circuit and on the current that can flow in the circuit.

Series resistors

ESAFJ

When we add resistors in series to a circuit:

- There is only one path for current to flow which ensures that the **current is the same at every point in the circuit**.
- The voltage is **divided** across the resistors. The voltage across the battery in the circuit is equal to the sum of voltages across the series resistors:

$$\boxed{V_{battery} = V_1 + V_2 + \ldots}$$

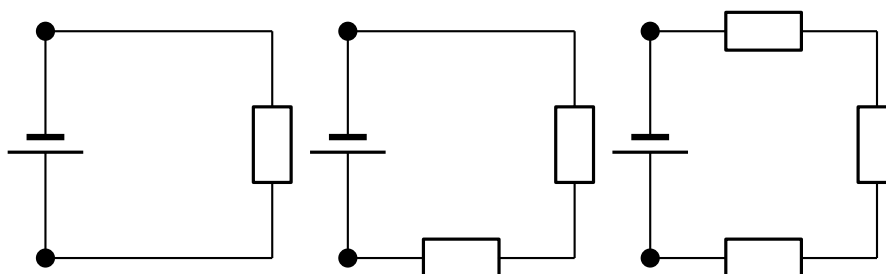
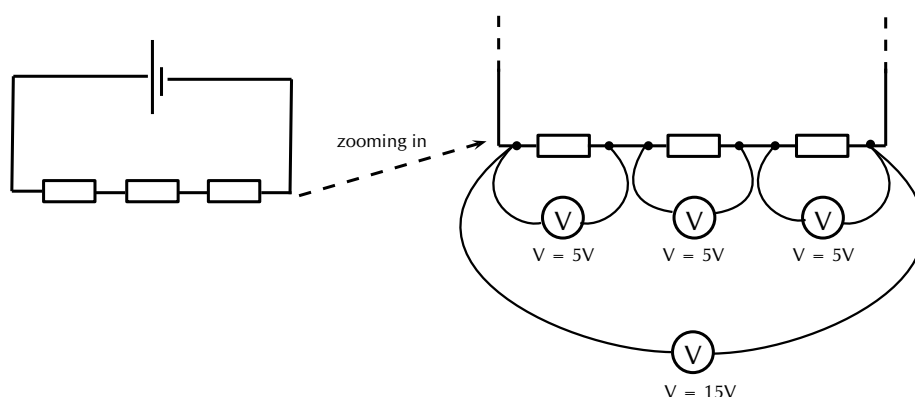
- The resistance to the flow of current **increases**. The total resistance, R_S is given by:

$$\boxed{R_S = R_1 + R_2 + \ldots}$$

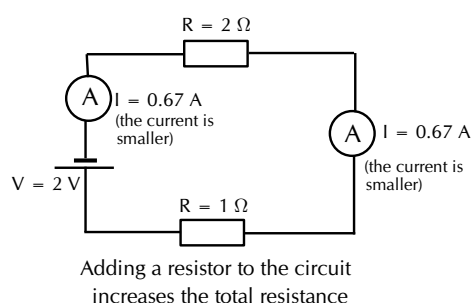
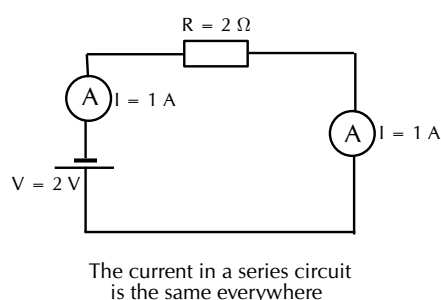
We will revisit each of these features of series circuits in more detail below.

When resistors are in series, one after the other, there is a potential difference across each resistor. The total potential difference across a set of resistors in series is the sum of the potential differences across each of the resistors in the set.

$$V_{battery} = V_1 + V_2 + \ldots$$

Look at the circuits below. If we measured the potential difference between the black dots in all of these circuits it would be the same as we saw earlier. So we now know the total potential difference is the same across one, two or three resistors. We also know that some work is required to make charge flow through each resistor.

Let us look at this in a bit more detail. In the picture below you can see what the different measurements for 3 identical resistors in series could look like. The total voltage across all three resistors is the sum of the voltages across the individual resistors. Resistors in series are known as voltage dividers because the total voltage across all the resistors is divided amongst the individual resistors.

Consider the diagram below. On the left there is a circuit with a single resistor and a battery. **No matter where we measure the current, it is the same in a series circuit**. On the right, we have added a second resistor in series to the circuit. The *total* resistance of the circuit has *increased* and you can see from the reading on the ammeter that the current in the circuit has decreased.

The current in a series circuit is the same everywhere

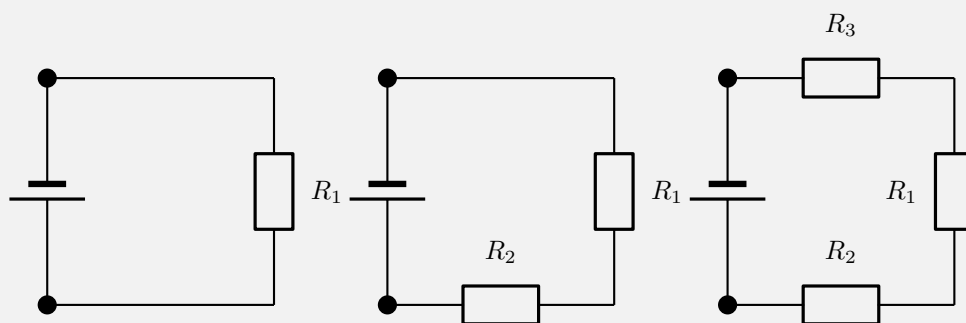
Adding a resistor to the circuit increases the total resistance

General experiment: *Voltage dividers*

Aim: Test what happens to the current and the voltage in series circuits when additional resistors are added.

Apparatus:

- A battery
- A voltmeter
- An ammeter
- Wires
- Resistors

Method:

- Construct each circuit shown below
- Measure the voltage across each resistor in the circuit.
- Measure the current before and after each resistor in the circuit.

Results and conclusions:

- Compare the sum of the voltages across all the resistors in each of the circuits.
- Compare the various current measurements within the same circuit.

The total resistance is equal to R_1 in the first circuit, to $R_1 + R_2$ in the second circuit and $R_1 + R_2 + R_3$ in the third circuit. In general, for resistors in series, the total resistance is given by:

$$R_S = R_1 + R_2 + \ldots$$

We know that the potential energy lost across a resistor is proportional to the resistance of the component because the higher the resistance the more work must be done to drive charge through the resistor.

Example 4: *Series resistors I*

QUESTION

A circuit contains two resistors in series. The resistors have resistance values of $5\ \Omega$ *and* $17\ \Omega$.

What is the total resistance in the circuit?

SOLUTION

Step 1 : ***Analyse the question***

We are told that the circuit is a series circuit and that we need to calculate the total resistance. The values of the two resistors have been given in the correct units, Ω.

Step 2 : ***Apply the relevant principles***

The total resistance for resistors in series is the sum of the individual resistances. We can use

$$R_S = R_1 + R_2 + \ldots$$

. We have only two resistors and we now the resistances. In this case we have that:

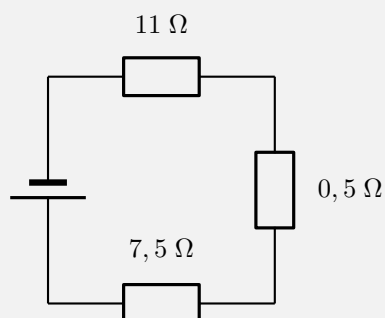
$$\begin{aligned} R_S &= R_1 + R_2 + \ldots \\ R_S &= R_1 + R_2 \\ &= 5\ \Omega + 17\ \Omega \\ &= 22\ \Omega \end{aligned}$$

Step 3 : ***Quote the final result***

The total resistance of the resistors in series is 22 Ω.

Example 5: Series resistors II

QUESTION

A circuit contains three resistors in series. The resistors have resistance values of $0,5\ \Omega$*,* $7,5\ \Omega$ *and* $11\ \Omega$*.*

What is the total resistance in the circuit?

SOLUTION

Step 1 : ***Analyse the question***

We are told that the circuit is a series circuit and that we need to calculate the total resistance. The values of the three resistors have been given in the correct units, Ω.

Step 2 : ***Apply the relevant principles***

The total resistance for resistors in series is the sum of the individual resistances. We can use

$$R_S = R_1 + R_2 + \ldots$$

. We have three resistors and we now the resistances. In this case we have that:

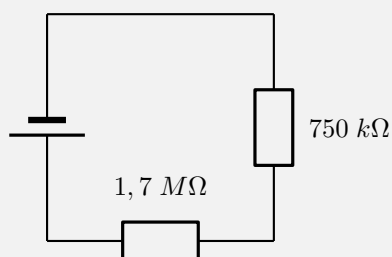
$$\begin{aligned} R_S &= R_1 + R_2 + \ldots \\ R_S &= R_1 + R_2 + R_3 \\ &= 0,5\ \Omega + 7,5\ \Omega + 11\ \Omega \\ &= 19\ \Omega \end{aligned}$$

Step 3 : ***Quote the final result***

The total resistance of the resistors in series is $19\ \Omega$.

Example 6: *Series resistors III*

QUESTION

A circuit contains two resistors in series. The resistors have resistance values of $750\ k\Omega$ *and* $1,7\ M\Omega$.

What is the total resistance in the circuit?

SOLUTION

Step 1 : ***Analyse the question***
We are told that the circuit is a series circuit and that we need to calculate the total resistance. The values of the two resistors have been given in the correct units, Ω.

Step 2 : ***Apply the relevant principles***
The total resistance for resistors in series is the sum of the individual resistances. We can use

$$R_S = R_1 + R_2 + \ldots$$

. We have only two resistors and we now the resistances. In this case

we have that:

$$\begin{aligned}R_S &= R_1 + R_2 + \ldots \\ R_S &= R_1 + R_2 \\ &= 750\ k\Omega + 1,7\ M\Omega \\ &= 750 \times 10^3\ \Omega + 1,7 \times 10^6\ \Omega \\ &= 0,75 \times 10^6\ \Omega + 1,7 \times 10^6\ \Omega \\ &= 2,45 \times 10^6\ \Omega = 2,45\ M\Omega\end{aligned}$$

Step 3 : ***Quote the final result***

The total resistance of the resistors in series is $2,45\ M\Omega$.

Parallel resistors

When we add resistors in parallel to a circuit:

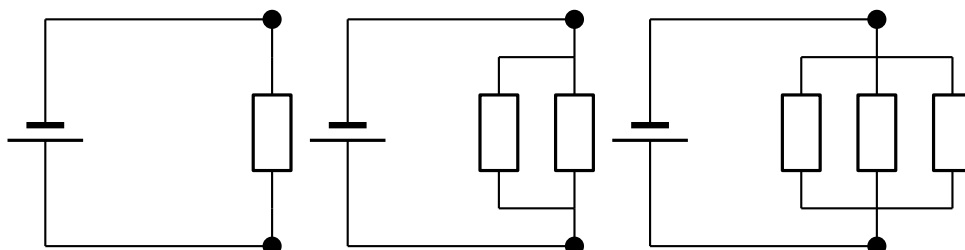
- There are more paths for current to flow which ensures that the **current splits across the different paths**.
- The voltage is **the same** across the resistors. The voltage across the battery in the circuit is equal to the voltage across each of the parallel resistors:

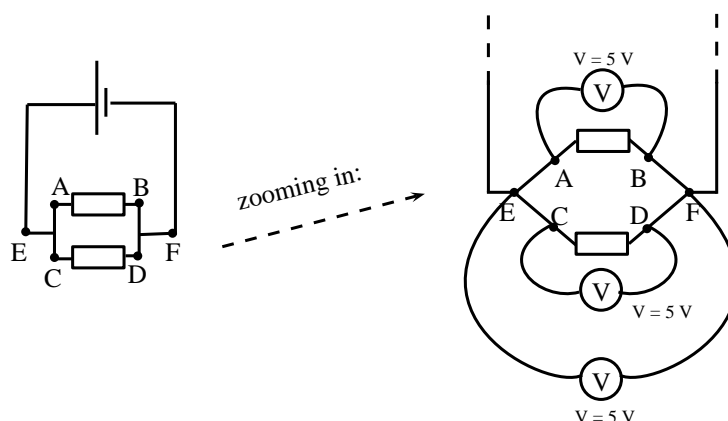
$$\boxed{V_{battery} = V_1 = V_2 = V_3 \ldots}$$

- The resistance to the flow of current **decreases**. The total resistance, R_P is given by:

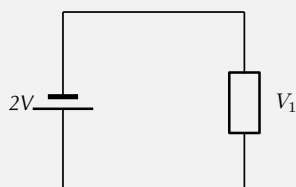
$$\boxed{\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots}$$

When resistors are connected in parallel the start and end points for all the resistors are the same. These points have the same potential energy and so the potential difference between them is the same no matter what is put in between them. You can have one, two or many resistors between the two points, the potential difference will not change. You can ignore whatever components are between two points in a circuit when calculating the difference between the two points.

Look at the following circuit diagrams. The battery is the same in all cases, all that changes is more resistors are added between the points marked by the black dots. If we were to measure the potential difference between the two dots in these circuits we would get the same answer for all three cases.

Lets look at two resistors in parallel more closely. When you construct a circuit you use wires and you might think that measuring the voltage in different places on the wires will make a difference. This is not true. The potential difference or voltage measurement will only be different if you measure a different set of components. All points on the wires that have no circuit components between them will give you the same measurements.

All three of the measurements shown in the picture below (i.e. A–B, C–D and E–F) will give you the same voltage. The different measurement points on the left have no components between them so there is no change in potential energy. Exactly the same applies to the different points on the right. When you measure the potential difference between the points on the left and right you will get the same answer.

Example 7: *Voltages I*

QUESTION

Consider this circuit diagram:

What is the voltage across the resistor in the circuit shown?

SOLUTION

Step 1 : ***Check what you have and the units***

We have a circuit with a battery and one resistor. We know the voltage across the battery. We want to find that voltage across the resistor.

$$V_{battery} = 2\text{ V}$$

Step 2 : ***Applicable principles***

We know that the voltage across the battery must be equal to the total voltage across all other circuit components.

$$V_{battery} = V_{total}$$

There is only one other circuit component, the resistor.

$$V_{total} = V_1$$

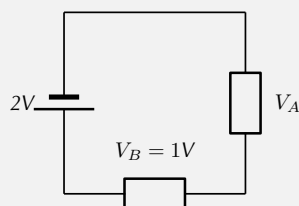
This means that the voltage across the battery is the same as the voltage across the resistor.

$$V_{battery} = V_{total} = V_1$$

$$V_{battery} = V_{total} = V_1$$
$$V_1 = 2V$$

Example 8: Voltages II

QUESTION

Consider this circuit:

What is the voltage across the unknown resistor in the circuit shown?

SOLUTION

Step 1 : ***Check what you have and the units***

We have a circuit with a battery and two resistors. We know the voltage across the battery and one of the resistors. We want to find that voltage across the resistor.

$$V_{battery} = 2V$$

$$V_B = 1V$$

Step 2 : ***Applicable principles***

We know that the voltage across the battery must be equal to the total voltage across all other circuit components that are in series.

$$V_{battery} = V_{total}$$

The total voltage in the circuit is the sum of the voltages across the individual resistors

$$V_{total} = V_A + V_B$$

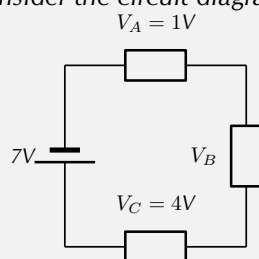
Using the relationship between the voltage across the battery and total voltage across the resistors

$$V_{battery} = V_{total}$$

$$V_{battery} = V_1 + V_{resistor}$$
$$2V = V_1 + 1V$$
$$V_1 = 1V$$

Example 9: Voltages III

QUESTION

Consider the circuit diagram:

What is the voltage across the unknown resistor in the circuit shown?

SOLUTION

Step 1 : ***Check what you have and the units***

We have a circuit with a battery and three resistors. We know the voltage across the battery and two of the resistors. We want to find that voltage across the unknown resistor.

$$\begin{aligned} V_{battery} &= 7V \\ V_{known} &= V_A + V_C \\ &= 1V + 4V \end{aligned}$$

Step 2 : ***Applicable principles***

We know that the voltage across the battery must be equal to the total voltage across all other circuit components that are in series.

$$V_{battery} = V_{total}$$

The total voltage in the circuit is the sum of the voltages across the

individual resistors

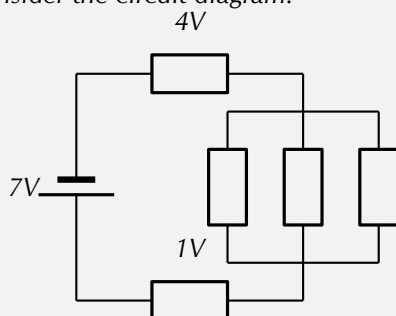
$$V_{total} = V_B + V_{known}$$

Using the relationship between the voltage across the battery and total voltage across the resistors

$$\begin{aligned} V_{battery} &= V_{total} \\ V_{battery} &= V_B + V_{known} \\ 7V &= V_B + 5V \\ V_B &= 2V \end{aligned}$$

Example 10: *Voltages IV*

QUESTION

Consider the circuit diagram:

What is the voltage across the parallel resistor combination in the circuit shown? Hint: the rest of the circuit is the same as the previous problem.

SOLUTION

Step 1 : ***Quick Answer***

The circuit is the same as the previous example and we know that the voltage difference between two points in a circuit does not depend on what is between them so the answer is the same as above $V_{parallel} = 2V$.

Step 2 : ***Check what you have and the units - long answer***

We have a circuit with a battery and five resistors (two in series and

three in parallel). We know the voltage across the battery and two of the resistors. We want to find that voltage across the parallel resistors, $V_{parallel}$.

$$V_{battery} = 7V$$

$$V_{known} = 1V + 4V$$

Step 3 : ***Applicable principles***

We know that the voltage across the battery must be equal to the total voltage across all other circuit components.

$$V_{battery} = V_{total}$$

Voltages only add algebraically for components in series. The resistors in parallel can be thought of as a single component which is in series with the other components and then the voltages can be added.

$$V_{total} = V_{parallel} + V_{known}$$

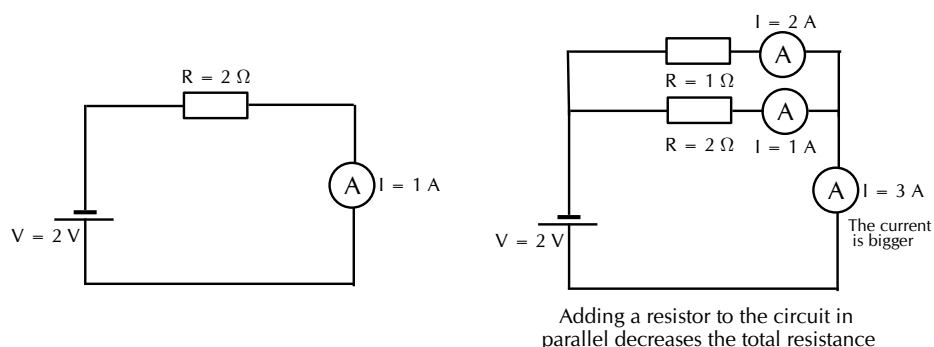
Using the relationship between the voltage across the battery and total voltage across the resistors

$$V_{battery} = V_{total}$$

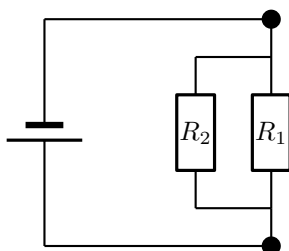
$$\begin{aligned} V_{battery} &= V_{parallel} + V_{known} \\ 7V &= V_{parallel} + 5V \\ V_{parallel} &= 2V \end{aligned}$$

In contrast to the series case, when we add resistors in parallel, we create **more paths** along which current can flow. By doing this we *decrease* the total resistance of the circuit!

Take a look at the diagram below. On the left we have the same circuit as in the previous section with a battery and a resistor. The ammeter shows a current of 1 A. On the right we have added a second resistor in parallel to the first resistor. This has increased the number of paths (branches) the charge can take through the circuit - the total resistance has decreased. You can see that the current in the circuit has increased. Also notice that the current in the different branches can be different.

Adding a resistor to the circuit in parallel decreases the total resistance

The total resistance of a number of parallel resistors is NOT the sum of the individual resistances as the overall resistance decreases with more paths for the current. The total resistance for parallel resistors is given by:

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$$

Let us consider the case where we have two resistors in parallel and work out what the final resistance would be. This situation is shown in the diagram below:

Applying the formula for the total resistance we have:

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$$

There are only two resistors

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2}$$

Add the fractions

$$\frac{1}{R_P} = \frac{1}{R_1} \times \frac{R_2}{R_2} + \frac{1}{R_2} \times \frac{R_1}{R_1}$$

$$\frac{1}{R_P} = \frac{R_2}{R_1 R_2} + \frac{R_1}{R_1 R_2}$$

Rearrange

$$\frac{1}{R_P} = \frac{R_2 + R_1}{R_1 R_2}$$
$$\frac{1}{R_P} = \frac{R_1 + R_2}{R_1 R_2}$$
$$R_P = \frac{R_1 R_2}{R_1 + R_2}$$

For any two resistors in parallel we now know that

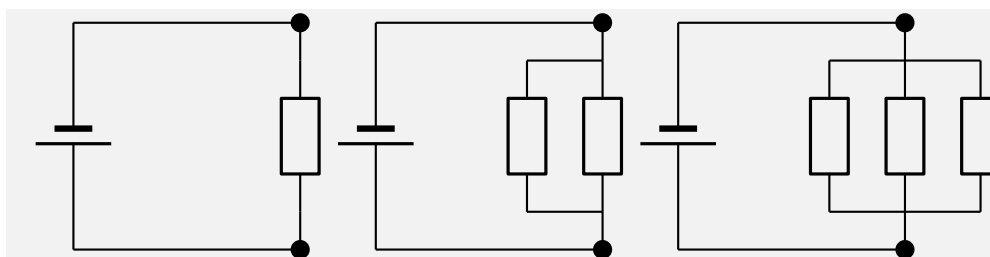
$$R_P = \frac{\text{product of resistances}}{\text{sum of resistances}} = \frac{R_1 R_2}{R_1 + R_2}$$

General experiment: *Current dividers*

Aim: Test what happens to the current and the voltage in series circuits when additional resistors are added.
Apparatus:

- A battery
- A voltmeter
- An ammeter
- Wires
- Resistors

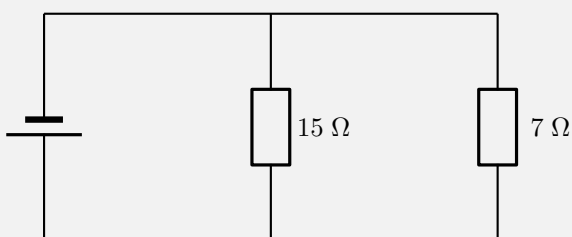
Method:

- Connect each circuit shown below
- Measure the voltage across each resistor in the circuit.
- Measure the current before and after each resistor in the circuit and before and after the parallel branches.

Results and conclusions:

- Compare the currents through individual resistors with each other.
- Compare the sum of the currents through individual resistors with the current before the parallel branches.
- Compare the various voltage measurements across the parallel resistors.

Example 11: *Parallel resistors I*

QUESTION

A circuit contains two resistors in parallel. The resistors have resistance values of $15\ \Omega$ *and* $7\ \Omega$.

What is the total resistance in the circuit?

SOLUTION

Step 1 : ***Analyse the question***

We are told that the resistors in the circuit are in parallel circuit and that we need to calculate the total resistance. The values of the two resistors have been given in the correct units, Ω.

Step 2 : ***Apply the relevant principles***

The total resistance for resistors in parallel has been shown to be the

product of the resistances divided by the sum. We can use

$$R_P = \frac{R_1 R_2}{R_1 + R_2}$$

. We have only two resistors and we now the resistances. In this case we have that:

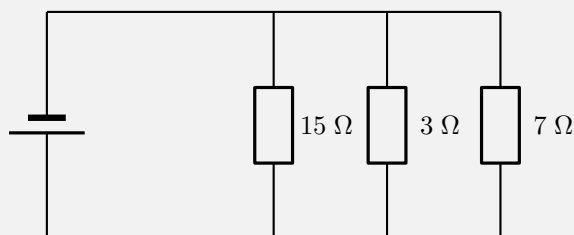
$$\begin{aligned} R_P &= \frac{R_1 R_2}{R_1 + R_2} \\ &= \frac{(15\ \Omega)(7\ \Omega)}{15\ \Omega + 7\ \Omega} \\ &= \frac{105\ \Omega^2}{22\ \Omega} \\ &= 4,77\ \Omega \end{aligned}$$

Step 3 : ***Quote the final result***

The total resistance of the resistors in parallel is $4,77\ \Omega$.

Example 12: Parallel resistors II

QUESTION

We add a third parallel resistor to the configuration (setup) in the previous example. The additional resistor has a resistance of .

What is the total resistance in the circuit?

SOLUTION

Step 1 : ***Analyse the question***

We are told that the resistors in the circuit are in parallel circuit and that we need to calculate the total resistance. The value of the additional resistor has been given in the correct units, Ω.

Step 2 : ***Apply the relevant principles***

The total resistance for resistors in parallel has been given as

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$$

. We have three resistors and we now the resistances. In this case we have that:

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$$

there are three resistors

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

add the fractions

$$\frac{1}{R_P} = \frac{1}{R_1} \times \frac{R_2R_3}{R_2R_3} + \frac{1}{R_2} \times \frac{R_1R_3}{R_1R_3} + \frac{1}{R_3} \times \frac{R_1R_2}{R_1R_2}$$

$$\frac{1}{R_P} = \frac{R_2R_3}{R_1R_2R_3} + \frac{R_1R_3}{R_1R_2R_3} + \frac{R_1R_2}{R_1R_2R_3}$$

rearrange

$$\frac{1}{R_P} = \frac{R_2R_3 + R_1R_3 + R_2R_3}{R_1R_2R_3}$$

$$R_P = \frac{R_1R_2R_3}{R_2R_3 + R_1R_3 + R_2R_3}$$

$$R_P = \frac{(15\ \Omega)(7\ \Omega)(3\ \Omega)}{(7\ \Omega)(3\ \Omega) + (15\ \Omega)(3\ \Omega) + (7\ \Omega)(15\ \Omega)}$$

$$R_P = \frac{315\ \Omega^3}{21\ \Omega^2 + 45\ \Omega^2 + 105\ \Omega^2}$$

$$R_P = \frac{315\ \Omega^3}{171\ \Omega^2}$$

$$R_P = 1,84\ \Omega$$

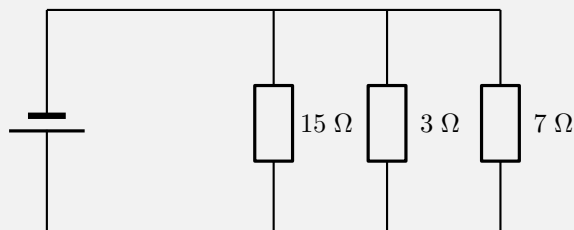
Step 3 : ***Quote the final result***

The total resistance of the resistors in parallel is $1,84\ \Omega$. It makes sense that this is less than in the previous example because we added an additional path and reduced the overall resistance in the circuit.

When calculating the resistance for complex resistor configurations, you can start with any combination of two resistors (in series or parallel) and calculate their total resistance. Then you can replace them with a single resistor that has the total resistance you calculated. Now use this new resistor in combination with any other resistor and repeat the process until there is only one resistor left. In the above example we could just have used the answer from the first example in parallel with the new resistor and we would get the same answer.

Example 13: Parallel resistors III

QUESTION

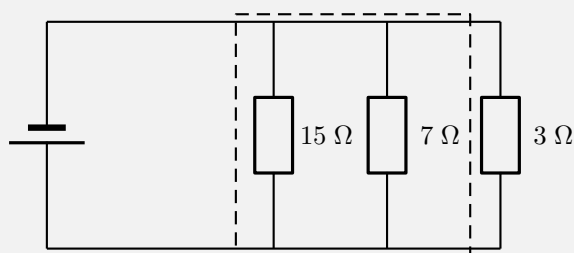
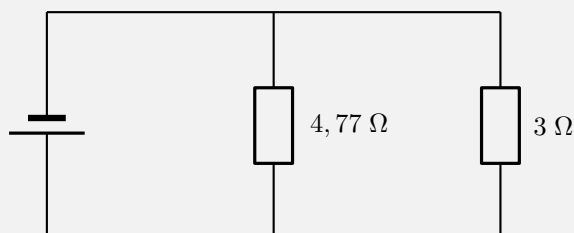
We add a third parallel resistor to the first parallel worked example configuration (setup). The additional resistor has a resistance of $3\ \Omega$.

What is the total resistance in the circuit?

SOLUTION

Step 1 : ***Analyse the question***

We are told that the resistors in the circuit are in parallel circuit and that we need to calculate the total resistance. The value of the additional resistor has been given in the correct units, Ω.

Step 2 : ***Apply the relevant principles***

We can swap the resistors around without changing the circuit:

We have already calculated the total resistance of the two resistors in the dashed box to be $4,77\ \Omega$. We can replace these two resistors with a single resistor of $4,77\ \Omega$ to get:

Step 3 : ***Calculate the total resistance for the next pair of resistors***

Then we use the formula for two parallel resistors again to get the total resistance for this new circuit:

$$\begin{aligned} R_P &= \frac{R_1 R_2}{R_1 + R_2} \\ &= \frac{(4,77\ \Omega)(3\ \Omega)}{4,77\ \Omega + 3\ \Omega} \\ &= \frac{14,31\ \Omega^2}{11,77\ \Omega} \\ &= 1,84\ \Omega \end{aligned}$$

Step 4 : ***Quote the final result***

The total resistance of the resistors in parallel is $1,84\ \Omega$. This is the same result as when we added all three resistors together at once.

Exercise 17 - 1

1. What is the unit of resistance called and what is its symbol?
2. Explain what happens to the total resistance of a circuit when resistors are added in series?
3. Explain what happens to the total resistance of a circuit when resistors are added in parallel?
4. Why do batteries go flat?

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(1.) 006u (2.) 006v (3.) 006w (4.) 006x

See simulation: (Simulation: VPfzj at www.everythingscience.co.za)

Chapter 17 | Summary

See the summary presentation (Presentation: VPftf at www.everythingscience.co.za)

- The potential difference across the terminals of a battery when it is **not** in a complete circuit is the electromotive force (emf) measured in volts (V).
- The potential difference across the terminals of a battery when it is in a complete circuit is the terminal potential difference measured in volts (V).
- Voltage is a measure of required/done to move a certain amount of charge and is equivalent to $\text{J} \cdot \text{C}^{-1}$.
- Current is the rate at which charge moves/flows and is measured in amperes (A) which is equivalent to $\text{C} \cdot \text{s}^{-1}$.
- Conventional current flows from the positive terminal of a battery, through a circuit, to the negative terminal.
- Ammeters measure current and must be connected in series.
- Voltmeters measure potential difference (voltage) and must be connected in parallel.
- Resistance is a measure of how much work must be done for charge to flow through a circuit element and is measured in ohms (Ω) and is equivalent to $\text{V} \cdot \text{A}^{-1}$.
- Resistance of circuit elements is related to the material from which they are made as well as the physical characteristics of length and cross-sectional area.
- Current is constant through resistors in series and they are called voltage dividers as the sum of the voltages is equal to the voltage across the entire set of resistors.
- The total resistance of resistors in series is the sum of the individual resistances, $R_S = R_1 + R_2 + \ldots$.
- Voltage is constant across resistors in parallel and they are called current divides because the sum of the current through each is the same as the total current through the circuit configuration.
- The total resistance of resistors in parallel is calculated by using $\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$ which is $R_P = \frac{R_1 R_2}{R_1 + R_2}$ for two parallel resistors.

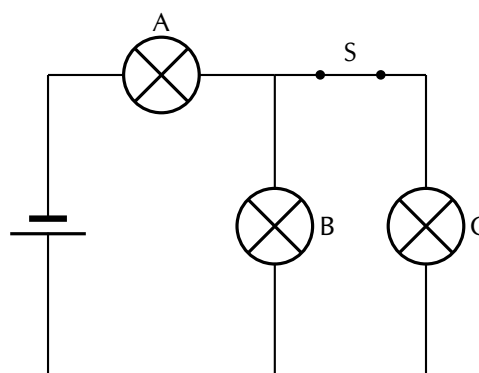
Physical Quantities		
Quantity	**Unit name**	**Unit symbol**
Potential difference (V)	volt	V
emf	volt	V
Voltage (V)	volt	V
Current (I)	ampere	A
Resistance (R)	ohm	Ω

Table 17.1: Units used in **electric circuits**

Chapter 17 End of chapter exercises

1. Write definitions for each of the following:
   a. resistor
   b. coulomb
   c. voltmeter
2. Draw a circuit diagram which consists of the following components:
   a. 2 batteries in parallel
   b. an open switch
   c. 2 resistors in parallel
   d. an ammeter measuring total current
   e. a voltmeter measuring potential difference across one of the parallel resistors
3. Complete the table below:

Quantity	Symbol	Unit of measurement	Symbol of unit
e.g. Distance	e.g. D	e.g. kilometre	e.g. km
Resistance			
Current			
Potential difference			

4. [SC 2003/11] The emf of a battery can best be explained as the ...
   a. rate of energy delivered per unit current
   b. rate at which charge is delivered
   c. rate at which energy is delivered
   d. charge per unit of energy delivered by the battery
5. [IEB 2002/11 HG1] Which of the following is the correct definition of the emf of a battery?
   a. It is the product of current and the external resistance of the circuit.
   b. It is a measure of the cell's ability to conduct an electric current.
   c. It is equal to the "lost volts" in the internal resistance of the circuit.
   d. It is the power supplied by the battery per unit current passing through the battery.
6. [IEB 2005/11 HG] Three identical light bulbs A, B and C are connected in an electric circuit as shown in the diagram below.

a. How bright is bulb A compared to B and C?
b. How bright are the bulbs after switch S has been opened?
c. How do the currents in bulbs A and B change when switch S is opened?

	Current in A	Current in B
(a)	decreases	increases
(b)	decreases	decreases
(c)	increases	increases
(d)	increases	decreases

7. [IEB 2004/11 HG1] When a current I is maintained in a conductor for a time of t, how many electrons with charge e pass any cross-section of the conductor per second?
   a. It
   b. It/e
   c. Ite
   d. e/It
8. If you have a circuit consisting of 4 resistors of equal resistance in series and the total voltage across all of them is 17 V, what is the voltage across each of them?
9. If you have a circuit consisting of 4 resistors of equal resistance in parallel and the total voltage across all of them is 17 V, what is the voltage across each of them?
10. In a circuit consisting of a battery and 3 resistors in series, what is the voltage across the first resistor if the voltage across the battery is 12 V and the voltages across the other two resistors is 3 V and 2 V respectively?
11. There are 3 resistors in parallel with resistances of 3 Ω, 4 Ω and 11 Ω. What is the total resistance of the parallel combination?
12. The same three resistors as above are now arranged in series, 3 Ω, 4 Ω and 11 Ω. What is the total resistance of the series combination?
13. The total resistance of two resistors in parallel is 3 Ω, the one resistor has a resistance of 5 Ω, what is the resistance of the other resistor?
14. In a series circuit there are 3 resistors with voltages of 2 V, 5 V and 8 V,

what is the voltage across the battery in the circuit?

15. In a parallel circuit there are 3 resistors with voltages of 2 V, 2 V and 2 V, what is the voltage across the battery in the circuit?

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(1.) 006y (2.) 006z (3.) 0070 (4.) 0071 (5.) 0072 (6.) 0073
(7.) 0074 (8.) 01uw (9.) 01ux (10.) 01uy (11.) 01uz (12.) 01v0
(13.) 01v1 (14.) 01v2 (15.) 01v3

Reactions in aqueous solution

18

Introduction

ESAFL

Many reactions in chemistry and all biological reactions (reactions in living systems) take place in water. We say that these reactions take place in aqueous solution. Water has many unique properties and is plentiful on Earth. For these reasons reactions in aqueous solutions occur frequently. In this chapter we will look at some of these reactions in detail. Almost all the reactions that occur in aqueous solutions involve ions. We will look at three main types of reactions that occur in aqueous solutions, namely precipitation reactions, acid-base reactions and redox reactions. Before we can learn about the types of reactions, we need to first look at ions in aqueous solutions and electrical conductivity. See introductory video: (Video: VPbls at www.everythingscience.co.za)

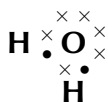
Ions in aqueous solution

ESAFM

Water is seldom pure. Because of the structure of the water molecule, substances can dissolve easily in it. This is very important because if water wasn't able to do this, life would not be possible on Earth. In rivers and the oceans for example, dissolved oxygen means that organisms (such as fish) are able to respire (breathe). For plants, dissolved nutrients are available in a form which they can absorb. In the human body, water is able to carry dissolved substances from one part of the body to another.

Dissociation in water

ESAFN

Water is a **polar molecule**. If we represent water using Lewis structures we will get the following:

You will notice that there are two electron pairs that do not take part in bonding. This side of the water molecule has a higher *electron density* than the other side where the hydrogen atoms are bonded. This side of the water molecule is *more negative* than the side where the hydrogen atoms are bonded. We say this side is the delta negative ($\delta-$) side and the hydrogen side is the delta positive ($\delta+$) side. This means that one part of the molecule has a slightly *positive* charge (positive pole) and the other part has a slightly *negative* charge (negative pole). We say such a molecule is a **dipole**. It has two poles. Figure 18.2 shows this.

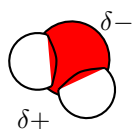



Figure 18.2: Water is a polar molecule

See video: VPbmr at www.everythingscience.co.za

Dissociation of sodium chloride in water ESAFO

It is the polar nature of water that allows ionic compounds to dissolve in it. In the case of sodium chloride (NaCl) for example, the positive sodium ions (Na^{+}) are attracted to the negative pole of the water molecule, while the negative chloride ions (Cl^{-}) are attracted to the positive pole of the water molecule. When sodium chloride is dissolved in water, the polar water molecules are able to work their way in between the individual ions in the lattice. The water molecules surround the negative chloride ions and positive sodium ions and pull them away into the solution. This process is called **dissociation**. Note that the positive side of the water molecule will be attracted to the negative chlorine ion and the negative side of the water molecule to the positive sodium ions. A simplified representation of this is shown in Figure 18.3. We say that dissolution of a substance has occurred when a substance dissociates or dissolves. Dissolving is a physical change that takes place. It can be reversed by removing (evaporating) the water.

DEFINITION: Dissociation

Dissociation is a general process in which ionic compounds separate into smaller ions, usually in a reversible manner.

DEFINITION: Dissolution

Dissolution or dissolving is the process where ionic crystals break up into ions in water.

DEFINITION: Hydration

Hydration is the process where ions become surrounded with water molecules.

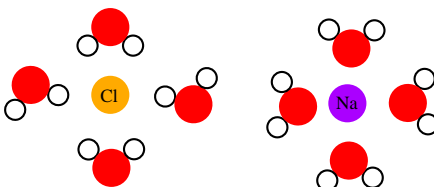
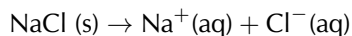
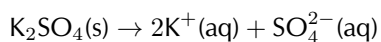
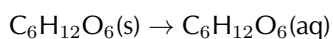



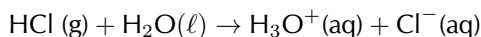
Figure 18.3: Sodium chloride dissolves in water

The dissolution of sodium chloride can be represented by the following equation:

$NaCl\ (s) \rightarrow Na^{+}(aq) + Cl^{-}(aq)$

The dissolution of potassium sulphate into potassium and sulphate ions is shown below as another example:

$K_2SO_4(s) \rightarrow 2K^{+}(aq) + SO_4^{2-}(aq)$

Remember that **molecular** substances (e.g. covalent compounds) may also dissolve, but most will not form ions. One example is glucose.

$C_6H_{12}O_6(s) \rightarrow C_6H_{12}O_6(aq)$

There are exceptions to this and some molecular substances *will* form ions when they dissolve. Hydrogen chloride for example can ionise to form hydrogen and chloride ions.

$HCl (g) + H_2O(\ell) \rightarrow H_3O^+(aq) + Cl^-(aq)$

You can try dissolving ionic compounds such as potassium permanganate, sodium hydroxide and potassium nitrate in water and observing what happens.

Exercise 18 - 1

1. For each of the following, say whether the substance is ionic or molecular.
   a. potassium nitrate (KNO_3)
   b. ethanol (C_2H_5OH)
   c. sucrose (a type of sugar) ($C_{12}H_{22}O_{11}$)
   d. sodium bromide (NaBr)
2. Write a balanced equation to show how each of the following ionic compounds dissociate in water.
   a. sodium sulphate (Na_2SO_4)
   b. potassium bromide (KBr)
   c. potassium permanganate ($KMnO_4$)
   d. sodium phosphate (Na_3PO_4)
3. Draw a diagram to show how KCl dissolves in water.

More practice video solutions or help at www.everythingscience.co.za

(1.) 0075 (2.) 0076 (3.) 0077

Electrolytes, ionisation and conductivity

ESAFP

You have learnt that water is a polar molecule and that it can dissolve ionic substances in water. When ions are present in water, the water is able to conduct electricity. The solution is known as an electrolyte.

DEFINITION: *Electrolyte*

An electrolyte is a substance that contains free ions and behaves as an electrically conductive medium.

Because electrolytes generally consist of ions in solution, they are also known as ionic solutions. A strong electrolyte is one where many ions are present in the solution and a weak electrolyte is one where few ions are present. Strong electrolytes are good conductors of electricity and weak electrolytes are weak conductors of electricity. Non-electrolytes do not conduct electricity at all. **Conductivity** in aqueous solutions, is a measure of the ability of water to conduct an electric current. The more **ions** there are in the solution, the higher its conductivity. Also the more ions there are in solution, the stronger the electrolyte.

Factors that affect the conductivity of electrolytes

The conductivity of an electrolyte is therefore affected by the following factors:

- The **concentration of ions** in solution. The higher the concentration of ions in solution, the higher its conductivity will be.
- The **type of substance** that dissolves in water. Whether a material is a strong electrolyte (e.g. potassium nitrate, KNO_3), a weak electrolyte (e.g. acetic acid, CH_3COOH) or a non-electrolyte (e.g. sugar, alcohol, oil) will affect the conductivity of water because the concentration of ions in solution will be different in each case. Strong electrolytes form ions easily, weak electrolytes do not form ions easily and non-electrolytes do not form ions in solution. See video: VPbon at www.everythingscience.co.za
- **Temperature.** The warmer the solution, the higher the solubility of the material being dissolved and therefore the higher the conductivity as well.

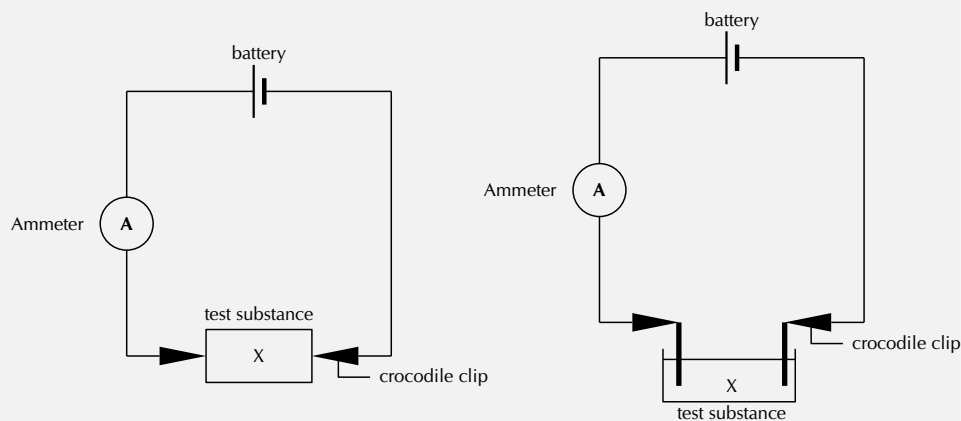
General experiment: *Electrical conductivity*

Aim: To investigate the electrical conductivities of different substances and solutions.

Apparatus:

- Solid salt (NaCl) crystals
- different liquids such as distilled water, tap water, seawater, sugar, oil and alcohol
- solutions of salts e.g. NaCl, KBr, $CaCl_2$, NH_4Cl
- a solution of an acid (e.g. HCl) and a solution of a base (e.g. NaOH)
- torch cells
- ammeter
- conducting wire, crocodile clips and 2 carbon rods.

Method:

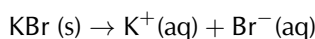
1. Set up the experiment by connecting the circuit as shown in the diagram below. In the diagram, X represents the substance or solution that you will be testing.
2. When you are using the solid crystals, the crocodile clips can be attached directly to each end of the crystal. When you are using solutions, two carbon rods are placed into the liquid and the clips are attached to each of the rods.
3. In each case, complete the circuit and allow the current to flow for about 30 seconds.
4. Observe whether the ammeter shows a reading.

Results: Record your observations in a table similar to the one below:

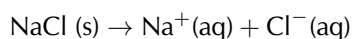
Test substance	Ammeter reading

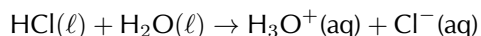
What do you notice? Can you explain these observations?
Conclusions: Solutions that contain free-moving ions are able to conduct electricity because of the movement of charged particles. Solutions that do not contain free-moving ions do not conduct electricity.

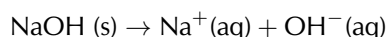
Remember that for electricity to flow, there needs to be a movement of charged particles e.g. ions. With the solid NaCl crystals, there was no flow of electricity recorded on the ammeter. Although the solid is made up of ions, they are held together very tightly within the crystal lattice and therefore no current will flow. Distilled water, oil and alcohol also don't conduct a current because they are *covalent compounds* and therefore do not contain ions.

The ammeter should have recorded a current when the salt solutions and the acid and base solutions were connected in the circuit. In solution, salts *dissociate* into their ions, so that these are free to move in the solution. Look at the following examples:
Dissociation of potassium bromide:

$$\text{KBr (s)} \rightarrow \text{K}^{+}\text{(aq)} + \text{Br}^{-}\text{(aq)}$$

Dissociation of table salt:

$$\text{NaCl (s)} \rightarrow \text{Na}^{+}\text{(aq)} + \text{Cl}^{-}\text{(aq)}$$

Ionisation of hydrochloric acid:

$$\text{HCl}(\ell) + \text{H}_2\text{O}(\ell) \rightarrow \text{H}_3\text{O}^{+}\text{(aq)} + \text{Cl}^{-}\text{(aq)}$$

Dissociation of sodium hydroxide:

$$\text{NaOH (s)} \rightarrow \text{Na}^{+}\text{(aq)} + \text{OH}^{-}\text{(aq)}$$

Precipitation reactions

Sometimes, ions in solution may react with each other to form a new substance that is *insoluble*. This is called a **precipitate**. The reaction is called a precipitation reaction.

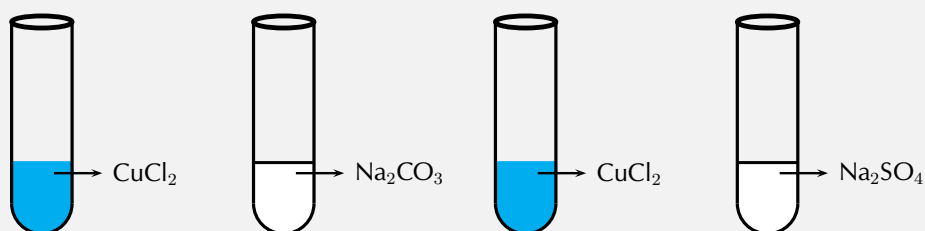
See video: VPbpr at www.everythingscience.co.za

DEFINITION: *Precipitate*

A precipitate is the solid that forms in a solution during a chemical reaction.

General experiment: *The reaction of ions in solution*

Aim: To investigate the reactions of ions in solutions.

Apparatus: 4 test tubes; copper(II) chloride solution; sodium carbonate solution; sodium sulphate solution

Method:

1. Prepare 2 test tubes with approximately 5 ml of dilute copper(II) chloride solution in each
2. Prepare 1 test tube with 5 ml sodium carbonate solution
3. Prepare 1 test tube with 5 ml sodium sulphate solution
4. Carefully pour the sodium carbonate solution into one of the test tubes containing copper(II) chloride and observe what happens
5. Carefully pour the sodium sulphate solution into the second test tube containing copper(II) chloride and observe what happens

Results:

1. A light blue precipitate forms when sodium carbonate reacts with copper(II) chloride.
2. No precipitate forms when sodium sulphate reacts with copper(II) chloride. The solution is light blue.

It is important to understand what happened in the previous demonstration. We will look at what happens in each reaction, step by step.
For **reaction 1** you have the following ions in your solution: Cu^{2+}, Cl^{-}, Na^{+} and CO_3^{2-}. A precipitate will form if any combination of cations and anions can become a solid. The following table summarises which combination will form solids (precipitates) in solution.

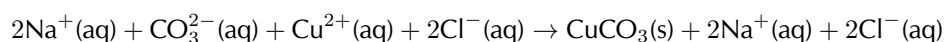
Salt	**Solubility**
Nitrates	All are **soluble**
Potassium, sodium and ammonium salts	All are **soluble**
Chlorides, bromides and iodides	All are **soluble** except silver, lead(II) and mercury(II) salts (e.g. silver chloride)
Sulphates	All are **soluble** except lead(II) sulphate, barium sulphate and calcium sulphate
Carbonates	All are **insoluble** except those of potassium, sodium and ammonium
Compounds with fluorine	Almost all are **soluble** except those of magnesium, calcium, strontium (II), barium (II) and lead (II)
Perchlorates and acetates	All are **soluble**
Chlorates	All are **soluble** except potassium chlorate
Metal hydroxides and oxides	Most are **insoluble**

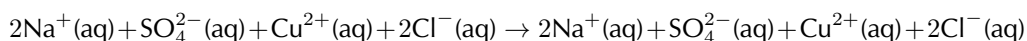
Tip

Salts of carbonates, phosphates, oxalates, chromates and sulphides are generally insoluble.

Table 18.1: General rules for the solubility of salts

If you look under carbonates in the table it states that all carbonates are **insoluble** except potassium sodium and ammonium. This means that Na_2CO_3 will dissolve in water or remain in solution, but $CuCO_3$ will form a precipitate. The precipitate that was observed in the reaction must therefore be $CuCO_3$. The balanced chemical equation is:

$$2Na^{+}(aq) + CO_3^{2-}(aq) + Cu^{2+}(aq) + 2Cl^{-}(aq) \rightarrow CuCO_3(s) + 2Na^{+}(aq) + 2Cl^{-}(aq)$$

Note that sodium chloride does not precipitate and we write it as ions in the equation. For **reaction 2** we have Cu^{2+}, Cl^{-}, Na^{+} and SO_4^{2-} in solution. Most chlorides and sulphates are soluble according to the table. The balanced chemical equation is:

$$2Na^{+}(aq)+SO_4^{2-}(aq)+Cu^{2+}(aq)+2Cl^{-}(aq) \rightarrow 2Na^{+}(aq)+SO_4^{2-}(aq)+Cu^{2+}(aq)+2Cl^{-}(aq)$$

Both of these reactions are ion exchange reactions.

Tests for anions

ESAFS

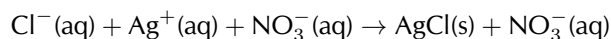
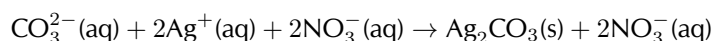
We often want to know which ions are present in solution. If we know which salts precipitate, we can derive tests to identify ions in solution. Given below are a few such tests.
See video: VPbqd at www.everythingscience.co.za

Test for a chloride

Prepare a solution of the unknown salt using distilled water and add a small amount of **silver nitrate** solution. If a white precipitate forms, the salt is either a chloride or a carbonate.

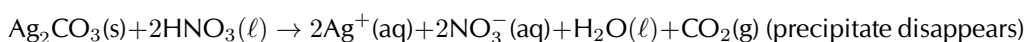
$$Cl^{-}(aq) + Ag^{+}(aq) + NO_3^{-}(aq) \rightarrow AgCl(s) + NO_3^{-}(aq)$$

(AgCl is white precipitate)

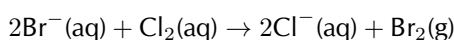
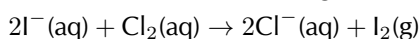
$$CO_3^{2-}(aq) + 2Ag^{+}(aq) + 2NO_3^{-}(aq) \rightarrow Ag_2CO_3(s) + 2NO_3^{-}(aq)$$

(Ag_2CO_3 is white precipitate)

The next step is to treat the precipitate with a small amount of **concentrated nitric acid**. If the precipitate remains unchanged, then the salt is a chloride. If carbon dioxide is formed and the precipitate disappears, the salt is a carbonate.

$AgCl(s) + HNO_3(\ell) \rightarrow$ (no reaction; precipitate is unchanged)

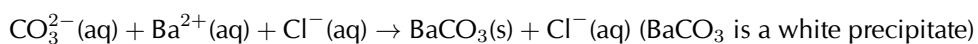
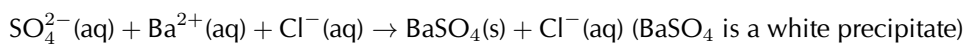
$Ag_2CO_3(s) + 2HNO_3(\ell) \rightarrow 2Ag^{+}(aq) + 2NO_3^{-}(aq) + H_2O(\ell) + CO_2(g)$ (precipitate disappears)

Test for bromides and iodides

As was the case with the chlorides, the bromides and iodides also form precipitates when they are reacted with silver nitrate. Silver chloride is a white precipitate, but the silver bromide and silver iodide precipitates are both pale yellow. To determine whether the precipitate is a bromide or an iodide, we use chlorine water and carbon tetrachloride (CCl_4).

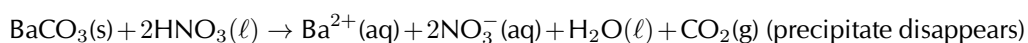
Chlorine water frees bromine gas from the bromide and colours the carbon tetrachloride a reddish brown.
$2Br^{-}(aq) + Cl_2(aq) \rightarrow 2Cl^{-}(aq) + Br_2(g)$

Chlorine water frees iodine gas from an iodide and colours the carbon tetrachloride purple.
$2I^{-}(aq) + Cl_2(aq) \rightarrow 2Cl^{-}(aq) + I_2(g)$

Test for a sulphate

Add a small amount of barium chloride solution to a solution of the test salt. If a white precipitate forms, the salt is either a sulphate or a carbonate.

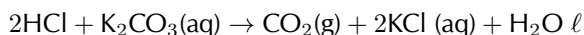
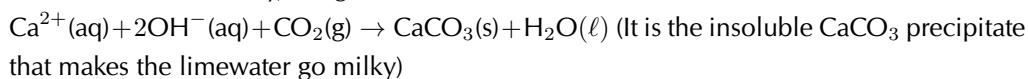
$SO_4^{2-}(aq) + Ba^{2+}(aq) + Cl^-(aq) \rightarrow BaSO_4(s) + Cl^-(aq)$ ($BaSO_4$ is a white precipitate)

$CO_3^{2-}(aq) + Ba^{2+}(aq) + Cl^-(aq) \rightarrow BaCO_3(s) + Cl^-(aq)$ ($BaCO_3$ is a white precipitate)

If the precipitate is treated with nitric acid, it is possible to distinguish whether the salt is a sulphate or a carbonate (as in the test for a chloride).

$BaSO_4(s) + HNO_3(\ell) \rightarrow$ (no reaction; precipitate is unchanged)

$BaCO_3(s) + 2HNO_3(\ell) \rightarrow Ba^{2+}(aq) + 2NO_3^-(aq) + H_2O(\ell) + CO_2(g)$ (precipitate disappears)

Test for a carbonate

If a sample of the dry salt is treated with a small amount of acid, the production of carbon dioxide is a positive test for a carbonate.

$$2HCl + K_2CO_3(aq) \rightarrow CO_2(g) + 2KCl\ (aq) + H_2O\ \ell$$

If the gas is passed through limewater (an aqueous solution of calcium hydroxide) and the solution becomes milky, the gas is carbon dioxide.
$Ca^{2+}(aq) + 2OH^-(aq) + CO_2(g) \rightarrow CaCO_3(s) + H_2O(\ell)$ (It is the insoluble $CaCO_3$ precipitate that makes the limewater go milky)

Exercise 18 - 2

1. Silver nitrate ($AgNO_3$) reacts with potassium chloride (KCl) and a white precipitate is formed.
   a. Write a balanced equation for the reaction that takes place. Include the state symbols.
   b. What is the name of the insoluble salt that forms?
   c. Which of the salts in this reaction are soluble?
2. Barium chloride reacts with sulphuric acid to produce barium sulphate and hydrochloric acid.
   a. Write a balanced equation for the reaction that takes place. Include the state symbols.
   b. Does a precipitate form during the reaction?
   c. Describe a test that could be used to test for the presence of barium sulphate in the products.

3. A test tube contains a clear, colourless salt solution. A few drops of silver nitrate solution are added to the solution and a pale yellow precipitate forms. Chlorine water and carbon tetrachloride were added, which resulted in a purple solution. Which one of the following salts was dissolved in the original solution? Write the balanced equation for the reaction that took place between the salt and silver nitrate.
   a. NaI
   b. KCl
   c. K_2CO_3
   d. Na_2SO_4

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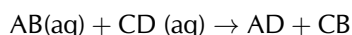
(1.) 0078 (2.) 0079 (3.) 007a

Other types of reactions ESAFT

We will look at two types of reactions that occur in aqueous solutions. These are ion-exchange reactions and redox reactions. Ion exchange reactions include precipitation reactions, gas forming reactions and acid-base reactions. Redox reactions are electron transfer reactions. It is important to remember the difference between these two types of reactions. In ion exchange reactions ions are exchanged, in electron transfer reactions electrons are transferred. These terms will be explained further in the following sections.

Ion exchange reactions ESAFU

Ion exchange reactions can be represented by:

$$AB(aq) + CD\ (aq) \rightarrow AD + CB$$

Either AD or CB may be a solid or a gas. When a solid forms this is known as a precipitation reaction. If a gas is formed then this may be called a gas forming reaction. Acid-base reactions are a special class of ion exchange reactions and we will look at them separately.

The formation of a precipitate or a gas helps to make the reaction happen. We say that the

reaction is driven by the formation of a precipitate or a gas. All chemical reactions will only take place if there is something to make them happen. For some reactions this happens easily and for others it is harder to make the reaction occur.

FACT

Ion exchange reactions are used in ion exchange chromatography. Ion exchange chromatography is used to purify water and as a means of softening water. Often when chemists talk about ion exchange, they mean ion exchange chromatography.

DEFINITION: Ion exchange reaction

A type of reaction where the positive ions exchange their respective negative ions due to a driving force.

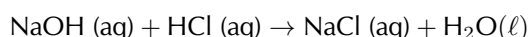
We have already looked at precipitation reactions.

Gas forming reactions

These reactions are similar to precipitation reactions with the exception that instead of a precipitate forming, a gas is formed instead. An example of a gas forming reaction is sodium carbonate in hydrochloric acid. The balanced equation for this reaction is:
$Na_2CO_3(s) + 2HCl(aq) \rightarrow CO_2(g) + 2NaCl(aq) + H_2O(\ell)$

Acid-base reactions

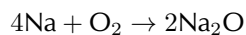
Acid-base reactions take place between acids and bases. In general, the products will be water and a salt (i.e. an ionic compound). An example of this type of reaction is:

$$NaOH\ (aq) + HCl\ (aq) \rightarrow NaCl\ (aq) + H_2O(\ell)$$

This is an special case of an ion exchange reaction since the sodium in the sodium hydroxide swaps places with the hydrogen in the hydrogen chloride forming sodium chloride. At the same time the hydroxide and the hydrogen combine to form water.

Redox reactions

Redox reactions involve the exchange of electrons. One ion loses electrons and becomes more positive, while the other ion gains electrons and becomes more negative. To decide if a redox reaction has occurred we look at the charge of the atoms, ions or molecules involved. If one of them has become more positive and the other one has become more

negative then a redox reaction has occurred. For example, sodium metal is oxidised to form sodium oxide (and sometimes sodium peroxide as well). The balanced equation for this is:

$$4Na + O_2 \rightarrow 2Na_2O$$

In the above reaction sodium and oxygen are both neutral and so have no charge. In the products however, the sodium atom has a charge of $+1$ and the oxygen atom has a charge of -2. This tells us that the sodium has lost electrons and the oxygen has gained electrons. Since one species has become more positive and one more negative we can conclude that a redox reaction has occurred. We could also say that electrons have been transferred from one species to the other. (In this case the electrons were transferred from the sodium to the oxygen).

General experiment: *Demonstration: Oxidation of sodium metal*

You will need a Bunsen burner, a small piece of sodium metal and a metal spatula. Light the Bunsen burner. Place the sodium metal on the spatula. Place the sodium in the flame. When the reaction finishes, you should observe a white powder on the spatula. This is a mixture of sodium oxide (Na_2O) and sodium peroxide (Na_2O_2).

Warning:
Sodium metal is very reactive. Sodium metal reacts vigorously with water and should never be placed in water. Be very careful when handling sodium metal.

General experiment: *Reaction types*

Aim: To use experiments to determine what type of reaction occurs.

Apparatus: Soluble salts (e.g. potassium nitrate, ammonium chloride, sodium carbonate, silver nitrate, sodium bromide); hydrochloric acid (HCl); sodium hydroxide (NaOH); bromothymol blue; zinc metal; copper (II) sulphate; beakers; test-tubes

Method:

1. For each of the salts, dissolve a small amount in water and observe what happens.
2. Try dissolving pairs of salts (e.g. potassium nitrate and sodium carbonate) in water and observe what happens.
3. Dissolve some sodium carbonate in hydrochloric acid and observe what happens.
4. Carefully measure out $20 cm^3$ of sodium hydroxide into a beaker.
5. Add some bromothymol blue to the sodium hydroxide
6. Carefully add a few drops of hydrochloric acid to the sodium hydroxide and swirl. Repeat until you notice the colour change.
7. Place the zinc metal into the copper sulphate solution and observe what happens.

Results: Answer the following questions:

1. What did you observe when you dissolved each of the salts in water?
2. What did you observe when you dissolved pairs of salts in the water?
3. What did you observe when you dissolved sodium carbonate in hydrochloric acid?
4. Why do you think we used bromothymol blue when mixing the hydrochloric acid and the sodium hydroxide? Think about the kind of reaction that occurred.
5. What did you observe when you placed the zinc metal into the copper sulphate?
6. Classify each reaction as either precipitation, gas forming, acid-base or redox.
7. What makes each reaction happen (i.e. what is the driving force)? Is it the formation of a precipitate or something else?
8. What criteria would you use to determine what kind of reaction occurs?
9. Try to write balanced chemical equations for each reaction

Conclusion: We can see how we can classify reactions by performing experiments.

In the experiment above, you should have seen how each reaction type differs from the others. For example, a gas forming reaction leads to bubbles in the solution, a precipitation reaction leads to a precipitate forming, an acid-base reaction can be seen by adding a suitable indicator and a redox reaction can be seen by one metal disappearing and a deposit forming in the solution.

Chapter 18 | Summary

See the summary presentation (Presentation: VPenn at www.everythingscience.co.za)

- The **polar** nature of water means that **ionic compounds** dissociate easily in aqueous solution into their component ions.
- Dissociation is a general process in which ionic compounds separate into smaller ions, usually in a reversible manner.
- Dissolution or dissolving is the process where ionic crystals break up into ions in water.
- Hydration is the process where ions become surrounded with water molecules.
- **Conductivity** is a measure of a solution's ability to conduct an electric current.
- An **electrolyte** is a substance that contains free ions and is therefore able to conduct an electric current. Electrolytes can be divided into **strong** and **weak** electrolytes, based on the extent to which the substance ionises in solution.
- A **non-electrolyte** cannot conduct an electric current because it does not contain free ions.
- The **type of substance**, the **concentration of ions** and the **temperature** of the solution affect its conductivity.
- There are three main types of reactions that occur in aqueous solutions. These are precipitation reactions, acid-base reactions and redox reactions.
- Precipitation and acid-base reactions are sometimes known as ion exchange reactions. Ion exchange reactions also include gas forming reactions. Ion exchange reactions are a type of reaction where the positive ions exchange their respective negative ions due to a driving force.
- A **precipitate** is formed when ions in solution react with each other to form an insoluble product. Solubility rules help to identify the precipitate that has been formed.
- A number of tests can be used to identify whether certain **anions** (chlorides, bromides, iodides, carbonates, sulphates) are present in a solution.
- An acid-base reaction is one in which an acid reacts with a base to form a salt and water.

- A redox reaction is one in which electrons are transferred from one substance to another.

Chapter 18 End of chapter exercises

1. Give one word for each of the following descriptions:
   a. the change in phase of water from a gas to a liquid
   b. a charged atom
   c. a term used to describe the mineral content of water
   d. a gas that forms sulphuric acid when it reacts with water
2. Match the information in column A with the information in column B by writing only the letter (A to I) next to the question number (1 to 7)

Column A	Column B
1. A polar molecule	A. H_2SO_4
2. Molecular solution	B. $CaCO_3$
3. Mineral that increases water hardness	C. NaOH
4. Substance that increases the hydrogen ion concentration	D. salt water
5. A strong electrolyte	E. calcium
6. A white precipitate	F. carbon dioxide
7. A non-conductor of electricity	G. potassium nitrate
	H. sugar water
	I. O_2

3. Explain the difference between a weak electrolyte and a strong electrolyte. Give a generalised equation for each.
4. What factors affect the conductivity of water? How do each of these affect the conductivity?
5. For each of the following substances state whether they are molecular or ionic. If they are ionic, give a balanced reaction for the dissociation in water.
   a. methane (CH_4)
   b. potassium bromide

c. carbon dioxide
d. hexane (C_6H_{14})
e. lithium fluoride (LiF)
f. magnesium chloride

6. Three test tubes (X, Y and Z) each contain a solution of an unknown potassium salt. The following observations were made during a practical investigation to identify the solutions in the test tubes:
A: A white precipitate formed when silver nitrate ($AgNO_3$) was added to test tube Z.
B: A white precipitate formed in test tubes X and Y when barium chloride ($BaCl_2$) was added.
C: The precipitate in test tube X dissolved in hydrochloric acid (HCl) and a gas was released.
D: The precipitate in test tube Y was insoluble in hydrochloric acid.
   a. Use the above information to identify the solutions in each of the test tubes X, Y and Z.
   b. Write a chemical equation for the reaction that took place in test tube X before hydrochloric acid was added.

(DoE Exemplar Paper 2 2007)

(1.) 007b (2.) 007c (3.) 007d (4.) 007e (5.) 007f (6.) 007g

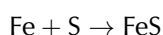
Quantitative aspects of chemical change

19

Atomic mass and the mole

ESAFW

An equation for a chemical reaction can provide us with a lot of useful information. It tells us what the reactants and the products are in the reaction, and it also tells us the ratio in which the reactants combine to form products. Look at the equation below:

$Fe + S \rightarrow FeS$

In this reaction, every atom of iron (Fe) will react with a single atom of sulphur (S) to form iron sulphide (FeS). However, what the equation does not tell us, is the **quantities** or the **amount** of each substance that is involved. You may for example be given a small sample of iron for the reaction. How will you know how many atoms of iron are in this sample? And how many atoms of sulphur will you need for the reaction to use up all the iron you have? Is there a way of knowing what mass of iron sulphide will be produced at the end of the reaction? These are all very important questions, especially when the reaction is an industrial one, where it is important to know the quantities of reactants that are needed, and the quantity of product that will be formed. This chapter will look at how to quantify the changes that take place in chemical reactions.

See introductory video: (Video: VPbrj at www.everythingscience.co.za)

The Mole

ESAFX

Sometimes it is important to know exactly how many particles (e.g. atoms or molecules) are in a sample of a substance, or what quantity of a substance is needed for a chemical reaction to take place.

The amount of substance is so important in chemistry that it is given its own name, which is the mole.

DEFINITION: Mole

The mole (abbreviation "mol") is the SI (Standard International) unit for "amount of substance".

The mole is a counting unit just like hours or days. We can easily count one second or one minute or one hour. If we want bigger units of time, we refer to days, months and years. Even longer time periods are centuries and millennia. The mole is even bigger than these numbers. The mole is $602\ 204\ 500\ 000\ 000\ 000\ 000\ 000$ or $6,022 \times 10^{23}$ particles. This is a *very* big number! We call this number Avogadro's number.

DEFINITION: Avogadro's number

The number of particles in a mole, equal to $6,022 \times 10^{23}$.

If we had this number of cold drink cans, then we could cover the surface of the earth to a depth of over 300 km! If you could count atoms at a rate of 10 million per second, then it would take you 2 billion years to count the atoms in one mole!

We use Avogadro's number and the mole in chemistry to help us quantify what happens in chemical reaction. The mole is a very special number. If we measure $12,0$ g of carbon we have one mole or $6,022 \times 10^{23}$ carbon atoms. $63,5$ g of copper is one mole of copper or $6,022 \times 10^{23}$ copper atoms. In fact, if we measure the relative atomic mass of any element on the periodic table, we have one mole of that element.

See video: VPbsf at www.everythingscience.co.za

FACT

The original hypothesis that was proposed by Amadeo Avogadro was that "equal volumes of gases, at the same temperature and pressure, contain the same number of molecules". His ideas were not accepted by the scientific community and it was only four years after his death, that his original hypothesis was accepted and that it became known as "Avogadro's Law". In honour of his contribution to science, the number of particles in one mole was named *Avogadro's number*.

Exercise 19 - 1

1. How many atoms are there in:

    a. 1 mole of a substance
    b. 2 moles of calcium
    c. 5 moles of phosphorus
    d. $24,3$ g of magnesium
    e. $24,0$ g of carbon

2. Complete the following table:

Element	Relative atomic mass (u)	Sample mass (g)	Number of moles in the sample
Hydrogen	$1,01$	$1,01$	
Magnesium	$24,3$	$24,3$	
Carbon	$12,0$	$24,0$	
Chlorine	$35,45$	$70,9$	
Nitrogen	$14,0$	$42,0$	

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(1.) 007h (2.) 007i

Molar Mass

ESAFY

DEFINITION: Molar mass

Molar mass (M) is the mass of 1 mole of a chemical substance. The unit for molar mass is **grams per mole** or g · mol^{-1}.

Note

You may sometimes see the molar mass written as M_m. We will use M in this book, but you should be aware of the alternate notation.

You will remember that when the mass, in grams, of an element is equal to its relative atomic mass, the sample contains one mole of that element. This mass is called the **molar mass** of that element.

It is worth remembering the following: On the periodic table, the relative atomic mass that is shown can be interpreted in two ways.

1. The mass (in grams) of a *single, average atom* of that element relative to the mass of an atom of carbon.
2. The average atomic mass of all the isotopes of that element. This use is the *relative atomic mass.*
3. The mass of *one mole of the element.* This third use is the molar mass of the element.

Element	**Relative atomic mass (u)**	**Molar mass ($g \cdot mol^{-1}$)**	**Mass of one mole of the element (g)**
Magnesium	$24,3$	$24,3$	$24,3$
Lithium	$6,94$	$6,94$	$6,94$
Oxygen	$16,0$	$16,0$	$16,0$
Nitrogen	$14,0$	$14,0$	$14,0$
Iron	$55,8$	$55,8$	$55,8$

Table 19.1: The relationship between relative atomic mass, molar mass and the mass of one mole for a number of elements.

Example 1: *Calculating the number of moles from mass*

QUESTION

Calculate the number of moles of iron (Fe) in an $11,7$ g sample.

SOLUTION

Step 1 : ***Find the molar mass of iron***

If we look at the periodic table, we see that the molar mass of iron is $55,8$ g · mol^{-1}. This means that 1 mole of iron will have a mass of $55,8$ g.

Step 2 : ***Find the mass of iron***

If 1 mole of iron has a mass of $55,8$ g, then: the number of moles of iron in $111,7$ g must be:

$$\begin{aligned} n &= \frac{111,7 \text{ g}}{55,8 \text{ g} \cdot \text{mol}^{-1}} \\ &= \frac{111,7 \text{ g} \cdot \text{mol}}{55,8 \text{ g}} \\ &= 2 \text{ mol} \end{aligned}$$

There are 2 moles of iron in the sample.

Example 2: *Calculating mass from moles*

QUESTION

You have a sample that contains 5 *moles of zinc.*

***a**. What is the mass of the zinc in the sample?*
***b**. How many atoms of zinc are in the sample?*

SOLUTION

Step 1 : ***Find the molar mass of zinc***

Molar mass of zinc is $65,4\ \text{g} \cdot \text{mol}^{-1}$, meaning that 1 mole of zinc has a mass of $65,4$ g.

Step 2 : ***Find the mass***

If 1 mole of zinc has a mass of $65,4$ g, then 5 moles of zinc has a mass of: $65,4\ \text{g} \times 5\ \text{mol} = 327\ \text{g}$ (answer to a)

Step 3 : ***Find the number of atoms***

$5\text{mol} \times 6,022 \times 10^{23}\ \text{atoms} \cdot \text{mol}^{-1} = 3,011 \times 10^{23}$ atoms (answer to b)

Exercise 19 - 2

1. Give the molar mass of each of the following elements:

a. hydrogen gas
b. nitrogen gas
c. bromine gas

2. Calculate the number of moles in each of the following samples:

a. $21,6$ g of boron (B)
b. $54,9$ g of manganese (Mn)
c. $100,3$ g of mercury (Hg)
d. 50 g of barium (Ba)
e. 40 g of lead (Pb)

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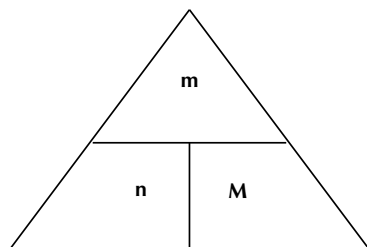
(1.) 007j (2.) 007k

An equation to calculate moles and mass ESAFZ

We can calculate molar mass as follows: $\text{molar mass (M)} = \frac{\text{mass (g)}}{\text{mole (mol)}}$
This can be rearranged to give the number of moles:

$$\mathbf{n} = \frac{\mathbf{m}}{\mathbf{M}}$$

The following diagram may help to remember the relationship between these three variables. You need to imagine that the horizontal line is like a division sign and that the vertical line is like a multiplication sign. So, for example, if you want to calculate M, then the remaining two letters in the triangle are m and n and m is above n with a division sign between them. Your calculation will then be $M = \frac{m}{n}$

Tip

Remember that when you use the equation $n = \frac{m}{M}$, the mass is always in grams (g) and molar mass is in grams per mol ($g \cdot mol^{-1}$). Always write the units next to any number you use in a formula or sum.

Example 3: Calculating moles from mass

QUESTION

Calculate the number of moles of copper there are in a sample that with a mass of 127 g.

SOLUTION

Step 1 : ***Write down the equation***

$$n = \frac{m}{M}$$

Step 2 : ***Find the moles***

$$n = \frac{127 \text{ g}}{63,5\text{g} \cdot \text{mol}^{-1}} = 2 \text{ mol}$$

There are 2 moles of copper in the sample.

Example 4: *Calculating atoms from mass*

QUESTION

Calculate the number of atoms there are in a sample of aluminium that with a mass of 81 *g.*

SOLUTION

Step 1 : ***Find the number of moles***

$$n = \frac{m}{M} = \frac{81 \text{ g}}{27,0 \text{ g} \cdot \text{mol}^{-1}} = 3 \text{ mol}$$

Step 2 : ***Find the number of atoms***

Number of atoms in 3 mol aluminium $= 3 \times 6,022 \times 10^{23}$

There are $1,8069 \times 10^{24}$ aluminium atoms in a sample of 81 g.

Exercise 19 - 3

1. Calculate the number of moles in each of the following samples:
   a. $5,6$ g of calcium
   b. $0,02$ g of manganese
   c. 40 g of aluminium
2. A lead sinker has a mass of 5 g.
   a. Calculate the number of moles of lead the sinker contains.
   b. How many lead atoms are in the sinker?
3. Calculate the mass of each of the following samples:
   a. $2,5$ mol magnesium
   b. 12 mol lithium
   c. $4,5 \times 10^{25}$ atoms of silicon

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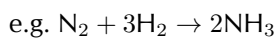
(1.) 007m (2.) 007n (3.) 007p

Compounds

So far, we have only discussed moles, mass and molar mass in relation to *elements*. But what happens if we are dealing with a compound? Do the same concepts and rules apply? The answer is *yes*. However, you need to remember that all your calculations will apply to the *whole compound*. So, when you calculate the **molar mass** of a covalent compound, you will need to add the molar mass of each atom in that compound. The number of moles will also apply to the whole molecule. For example, if you have one mole of nitric acid (HNO_3) the molar mass is $63,01$ g · mol^{-1} and there are $6,022 \times 10^{23}$ molecules of nitric acid. For network structures we have to use the formula mass. This is the mass of all the atoms in **one formula unit** of the compound. For example, one mole of sodium chloride (NaCl) has a formula mass of $63,01$ g · mol^{-1} and there are $6,022 \times 10^{23}$ molecules of sodium chloride in one formula unit.

In a balanced chemical equation, the number that is written in front of the element or compound, shows the **mole ratio** in which the reactants combine to form a product. If there are no numbers in front of the element symbol, this means the number is '1'.

See video: VPezc at www.everythingscience.co.za

e.g. $N_2 + 3H_2 \rightarrow 2NH_3$

In this reaction, 1 mole of nitrogen molecules reacts with 3 moles of hydrogen molecules to produce 2 moles of ammonia molecules.

Example 5: *Calculating molar mass*

QUESTION

Calculate the molar mass of H_2SO_4.

SOLUTION

Step 1 : ***Give the molar mass for each element***

$$\text{Hydrogen} = 1,01\ \text{g} \cdot \text{mol}^{-1}$$
$$\text{Sulphur} = 32,1\ \text{g} \cdot \text{mol}^{-1}$$
$$\text{Oxygen} = 16,0\ \text{g} \cdot \text{mol}^{-1}$$

Step 2 : ***Work out the molar mass of the compound***

$$M_{(H_2SO_4)} = (2 \times 1,01\ \text{g} \cdot \text{mol}^{-1}) + (32,1\ \text{g} \cdot \text{mol}^{-1}) + (4 \times 16,0\ \text{g} \cdot \text{mol}^{-1}) = 98,12\ \text{g} \cdot \text{mol}^{-1}$$

Example 6: *Calculating moles from mass*

QUESTION

Calculate the number of moles in 1 kg of $MgCl_2$.

SOLUTION

Step 1 : ***Convert mass into grams***

$$m = 1 \text{ kg} \times 1\ 000 = 1\ 000 \text{ g}$$

Step 2 : ***Calculate the molar mass***

$$M_{(\text{MgCl}_2)} = 24,3 \text{ g} \cdot \text{mol}^{-1} + (2 \times 35,45 \text{ g} \cdot \text{mol}^{-1}) = 95,2\text{g} \cdot \text{mol}^{-1}$$

Step 3 : ***Find the number of moles***

$$n = \frac{1\ 000 \text{ g}}{95,2 \text{ g} \cdot \text{mol}^{-1}} = 10,5 \text{ mol}$$

There are $10,5$ moles of magnesium chloride in a 1 kg sample.

Group Discussion: Understanding moles, molecules and Avogadro's number

Divide into groups of three and spend about 20 minutes answering the following questions together:

1. What are the units of the mole? Hint: Check the definition of the mole.
2. You have a 46 g sample of nitrogen dioxide (NO_2)
   - **a**. How many **moles** of NO_2 are there in the sample?
   - **b**. How many moles of nitrogen atoms are there in the sample?
   - **c**. How many moles of oxygen atoms are there in the sample?
   - **d**. How many **molecules** of NO_2 are there in the sample?
   - **e**. What is the difference between a mole and a molecule?
3. The exact size of **Avogadro's number** is sometimes difficult to imagine.
   - **a**. Write down Avogadro's number without using scientific notation.
   - **b**. How long would it take to count to Avogadro's number? You can assume that you can count two numbers in each second.

Exercise 19 - 4

1. Calculate the molar mass of the following chemical compounds:

a. KOH
b. $FeCl_3$
c. $Mg(OH)_2$

2. How many moles are present in:
   a. 10 g of Na_2SO_4
   b. 34 g of $Ca(OH)_2$
   c. $2,45 \times 10^{23}$ molecules of CH_4?
3. For a sample of $0,2$ moles of magnesium bromide ($MgBr_2$), calculate:
   a. the number of moles of Mg^{2+} ions
   b. the number of moles of Br^- ions
4. You have a sample containing 3 mol of calcium chloride.
   a. What is the chemical formula of calcium chloride?
   b. How many calcium atoms are in the sample?
5. Calculate the mass of:
   a. 3 moles of NH_4OH
   b. $4,2$ moles of $Ca(NO_3)_2$

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(1.) 007q (2.) 007r (3.) 007s (4.) 007t (5.) 007u

Composition

Knowing either the empirical or molecular formula of a compound, can help to determine its composition in more detail. The opposite is also true. Knowing the *composition* of a substance can help you to determine its formula. There are four different types of composition problems that you might come across:

1. Problems where you will be **given the formula** of the substance and asked to **calculate** the **percentage by mass** of each element in the substance.
2. Problems where you will be **given the percentage composition** and asked to **calculate the formula**.
3. Problems where you will be **given the products** of a chemical reaction and asked to **calculate the formula** of one of the reactants. These are often referred to as combustion analysis problems.

4. Problems where you will be asked to **find** number of moles of **waters of crystallisation**.

The following worked examples will show you how to do each of these.

See video: VPbue at www.everythingscience.co.za

Example 7: Calculating the percentage by mass of elements in a compound

QUESTION

Calculate the percentage that each element contributes to the overall mass of sulphuric acid (H_2SO_4).

SOLUTION

Step 1 : ***Calculate the molar masses***

$$\text{Hydrogen} = 2 \times 1,01 = 2,02 \text{ g} \cdot \text{mol}^{-1}$$
$$\text{Sulphur} = 32,1 \text{ g} \cdot \text{mol}^{-1}$$
$$\text{Oxygen} = 4 \times 16,0 = 64,0 \text{ g} \cdot \text{mol}^{-1}$$

Step 2 : ***Use the calculations in the previous step to calculate the molecular mass of sulphuric acid.***

$$\text{Mass} = 2,02 \text{ g}\cdot\text{mol}^{-1} + 32,1 \text{ g}\cdot\text{mol}^{-1} + 64,0 \text{ g}\cdot\text{mol}^{-1} = 98,12 \text{ g}\cdot\text{mol}^{-1}$$

Step 3 : ***Use the equation***

$$\text{Percentage by mass} = \frac{\text{atomic mass}}{\text{molecular mass of } H_2SO_4} \times 100\%$$

Hydrogen

$$\frac{2,02 \text{ g} \cdot \text{mol}^{-1}}{98,12 \text{ g} \cdot \text{mol}^{-1}} \times 100\% = 2,0587\%$$

Sulphur

$$\frac{32,1 \text{ g} \cdot \text{mol}^{-1}}{98,12 \text{ g} \cdot \text{mol}^{-1}} \times 100\% = 32,7150\%$$

Oxygen

$$\frac{64,0 \text{ g} \cdot \text{mol}^{-1}}{98,12 \text{ g} \cdot \text{mol}^{-1}} \times 100\% = 65,2263\%$$

(You should check at the end that these percentages add up to 100%!)

In other words, in one molecule of sulphuric acid, hydrogen makes up $2,06\%$ of the mass of the compound, sulphur makes up $32,71\%$ and oxygen makes up $65,23\%$.

Example 8: *Determining the empirical formula of a compound*

QUESTION

A compound contains $52,2\%$ carbon (C), $13,0\%$ hydrogen (H) and $34,8\%$ oxygen (O). Determine its empirical formula.

SOLUTION

Step 1 : ***Give the masses***

Carbon $= 52,2$ g, hydrogen $= 13,0$ g and oxygen $= 34,8$ g

Step 2 : ***Calculate the number of moles***

$$n = \frac{m}{M}$$

Therefore:

$$n\,(\text{Carbon}) = \frac{52,2\ \text{g}}{12,0\ \text{g}\cdot\text{mol}^{-1}} = 4,35\text{mol}$$

$$n\,(\text{Hydrogen}) = \frac{13,0\ \text{g}}{1,01\ \text{g}\cdot\text{mol}^{-1}} = 12,871\text{mol}$$

$$n\,(\text{Oxygen}) = \frac{34,8\ \text{g}}{16,0\ \text{g}\cdot\text{mol}^{-1}} = 2,175\text{mol}$$

Step 3 : ***Find the smallest number of moles***

Use the ratios of molar numbers calculated above to find the empirical formula.

$$\text{units in empirical formula} = \frac{\text{moles of this element}}{\text{smallest number of moles}}$$

In this case, the smallest number of moles is $2,175$. Therefore:

Carbon

$$\frac{4,35}{2,175} = 2$$

Hydrogen

$$\frac{12,871}{2,175} = 6$$

Oxygen

$$\frac{2,175}{2,175} = 1$$

Therefore the empirical formula of this substance is: C_2H_6O.

Example 9: *Determining the formula of a compound*

QUESTION

207 g of lead combines with oxygen to form 239 g of a lead oxide. Use this information to work out the formula of the lead oxide (Relative atomic masses: Pb = $207,2$ u and O = $16,0$ u).

SOLUTION

Step 1 : ***Find the mass of oxygen***

$$239 \text{ g} - 207 \text{ g} = 32 \text{ g}$$

Step 2 : ***Find the moles of oxygen***

$$n = \frac{m}{M}$$

Lead

$$n = \frac{207 \text{ g}}{207,2 \text{ g} \cdot \text{mol}^{-1}} = 1 \text{ mol}$$

Oxygen

$$n = \frac{32 \text{ g}}{16,0 \text{ g} \cdot \text{mol}^{-1}} = 2 \text{ mol}$$

Step 3 : ***Find the mole ratio***

The mole ratio of Pb : O in the product is $1 : 2$, which means that for every atom of lead, there will be two atoms of oxygen. The formula of the compound is PbO_2.

Example 10: *Empirical and molecular formula*

QUESTION

Vinegar, which is used in our homes, is a dilute form of acetic acid. A sample of acetic acid has the following percentage composition: $39,9\%$ carbon, $6,7\%$ hydrogen and $53,4\%$ oxygen.

1. *Determine the empirical formula of acetic acid.*
2. *Determine the molecular formula of acetic acid if the molar mass of acetic acid is $60,06$ g · mol^{-1}.*

SOLUTION

Step 1 : ***Find the mass***

In 100 g of acetic acid, there is $39,9$ g C, $6,7$ g H and $53,4$ g O

Step 2 : ***Find the moles***

$$n = \frac{m}{M}$$

$$n_C = \frac{39,9 \text{ g}}{12,0 \text{ g} \cdot \text{mol}^{-1}} = 3,325 \text{ mol}$$
$$n_H = \frac{6,7 \text{ g}}{1,01 \text{ g} \cdot \text{mol}^{-1}} = 6,6337 \text{ mol}$$
$$n_O = \frac{53,4 \text{ g}}{16,0 \text{ g} \cdot \text{mol}^{-1}} = 3,3375 \text{ mol}$$

Step 3 : ***Find the empirical formula***

C : H : O

$3,325 : 6,6337 : 3,3375$

$1 : 2 : 1$

Empirical formula is CH_2O

Step 4 : ***Find the molecular formula***

The molar mass of acetic acid using the empirical formula is $30,02$ g $\cdot$ mol^{-1}. However the question gives the molar mass as $60,06$ g $\cdot$ mol^{-1}. Therefore the actual number of moles of each element must be double what it is in the empirical formula ($\frac{60,06}{30,02} = 2$). The molecular formula is therefore $C_2H_4O_2$ or CH_3COOH

Example 11: *Waters of crystallisation*

QUESTION

Aluminium trichloride ($AlCl_3$) is an ionic substance that forms crystals in the solid phase. Water molecules may be trapped inside the crystal lattice. We represent this as: $AlCl_3 \cdot nH_2O$. Carine heated some aluminium trichloride crystals until all the water had evaporated and found that the mass after heating was $2,8$ g. The mass before heating was 5 g. What is the number of moles of water molecules in the

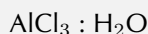
aluminium trichloride before heating?

SOLUTION

Step 1 : ***Find the number of water molecules***

We first need to find n, the number of water molecules that are present in the crystal. To do this we first note that the mass of water lost is $5 \text{ g} - 2,8 \text{ g} = 2,2 \text{ g}$.

Step 2 : ***Find the mass ratio***

The mass ratio is:

$AlCl_3 : H_2O$

$$2,8 : 2,2$$

Step 3 : ***Find the mole ratio***

To work out the mole ratio we divide the mass ratio by the molecular mass of each species:

$$AlCl_3 : H_2O$$

$$\frac{2,8 \text{ g}}{133,35 \text{ g} \cdot \text{mol}^{-1}} : \frac{2,2 \text{ g}}{18,02 \text{ g} \cdot \text{mol}^{-1}}$$

$$0,02099\ldots : 0,12\ldots$$

Next we convert the ratio to whole numbers by dividing both sides by the smaller amount:

$$AlCl_3 : H_2O$$

$$0,020997375 : 0,12208657$$

$$\frac{0,021}{0,021} : \frac{0,122}{0,021}$$

$$1 : 6$$

The mole ratio of aluminium trichloride to water is: $1 : 6$

Step 4 : ***Write the final answer***

And now we know that there are 6 moles of water molecules in the crystal. The formula is $AlCl_3 \cdot 6H_2O$.

We can perform experiments to determine the composition of substances. For example, blue copper sulphate ($CuSO_4$) crystals contain water. On heating the waters of crystallisation evaporate and the blue crystals become white. By weighing the starting and ending products, we can determine the amount of water that is in copper sulphate. Another example is reducing copper oxide to copper.

Exercise 19 - 5

1. Calcium chloride is produced as the product of a chemical reaction.
   a. What is the formula of calcium chloride?
   b. What is the percentage mass of each of the elements in a molecule of calcium chloride?
   c. If the sample contains 5 g of calcium chloride, what is the mass of calcium in the sample?
   d. How many moles of calcium chloride are in the sample?
2. 13 g of zinc combines with $6,4$ g of sulphur.
   a. What is the empirical formula of zinc sulphide?
   b. What mass of zinc sulphide will be produced?
   c. What is the percentage mass of each of the elements in zinc sulphide?
   d. The molar mass of zinc sulphide is found to be $97,44$ g $\cdot$ mol^{-1}. Determine the molecular formula of zinc sulphide.
3. A calcium mineral consisted of $29,4\%$ calcium, $23,5\%$ sulphur and $47,1\%$ oxygen by mass. Calculate the empirical formula of the mineral.
4. A chlorinated hydrocarbon compound was analysed and found to consist of $24,24\%$ carbon, $4,04\%$ hydrogen and $71,72\%$ chlorine. From another experiment the molecular mass was found to be 99 g$\cdot$mol^{-1}. Deduce the empirical and molecular formula.
5. Magnesium sulphate has the formula $MgSO_4 \cdot n\ H_2O$. A sample containing $5,0$ g of magnesium sulphate was heated until all the water had evaporated. The final mass was found to be $2,6$ g. How many water molecules were in the original sample?

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(1.) 007v (2.) 007w (3.) 007x (4.) 007y (5.) 007z

Amount of substance ESAGC

Molar Volumes of Gases ESAGD

DEFINITION: Molar volume of gases

One mole of gas occupies $22,4$ dm^3 at standard temperature and pressure.

Note

Standard temperature and pressure (S.T.P.) is defined as a temperature of $273,15$ K and a pressure of $0,986$ atm.

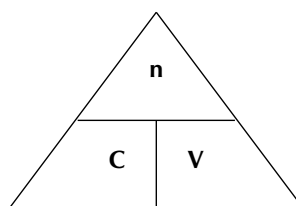
This applies to any gas that is at standard temperature and pressure. In grade 11 you will learn more about this and the gas laws.

For example, 2 mol of H_2 gas will occupy a volume of $44,8$ dm^3 at standard temperature and pressure (S.T.P.). and $67,2$ dm^3 of ammonia gas (NH_3) contains 3 mol of ammonia.

Molar concentrations of liquids ESAGE

A typical solution is made by dissolving some solid substance in a liquid. The amount of substance that is dissolved in a given volume of liquid is known as the **concentration** of the liquid. Mathematically, concentration (C) is defined as moles of solute (n) per unit volume (V) of solution.

See video: VPbur at www.everythingscience.co.za

$$C = \frac{n}{V}$$

For this equation, the units for volume are dm^3 (which is equal to litres). Therefore, the unit of concentration is $mol \cdot dm^{-3}$.

DEFINITION: Concentration

Concentration is a measure of the amount of solute that is dissolved in a given volume of liquid. It is measured in $mol \cdot dm^{-3}$.

Example 12: *Concentration Calculations 1*

QUESTION

If $3,5$ g of sodium hydroxide (NaOH) is dissolved in $2,5$ dm^3 of water, what is the concentration of the solution in $mol \cdot dm^{-3}$?

SOLUTION

Step 1 : ***Find the number of moles of sodium hydroxide***

$$n = \frac{m}{M} = \frac{3,5 \text{ g}}{40,01 \text{ g} \cdot \text{mol}^{-1}} = 0,0875 \text{ mol}$$

Step 2 : ***Calculate the concentration***

$$C = \frac{n}{V} = \frac{0,0875 \text{ mol}}{2,5 \text{ dm}^3} = 0,035 \text{ mol} \cdot \text{dm}^{-3}$$

The concentration of the solution is $0,035$ $mol \cdot dm^{-3}$.

Example 13: *Concentration Calculations 2*

QUESTION

You have a 1 dm^3 container in which to prepare a solution of potassium permanganate ($KMnO_4$). What mass of $KMnO_4$ is needed to make a solution with a concentration of $0,2$ mol · dm^{-3}?

SOLUTION

Step 1 : ***Calculate the number of moles***

$C = \frac{n}{V}$ therefore:

$$n = C \times V = 0,2 \text{ mol} \cdot \text{dm}^{-3} \times 1\text{dm}^{-3} = 0,2 \text{ mol}$$

Step 2 : ***Find the mass***

$m = n \times M = 0,2 \text{ mol} \times 158 \text{ g} \cdot \text{mol}^{-1} = 31,6 \text{ g}$

The mass of $KMnO_4$ that is needed is $31,6$ g.

Example 14: *Concentration Calculations 3*

QUESTION

How much sodium chloride (in g) will one need to prepare 500 cm^3 of solution with a concentration of $0,01$ mol · dm^{-3}?

SOLUTION

Step 1 : ***Convert the given volume to the correct units***

$$V = 500\text{cm}^3 \frac{1 \text{ dm}^3}{1000 \text{ cm}^3} = 0,5 \text{ dm}^3$$

Step 2 : ***Find the number of moles***

$n = C \times V = 0,01\ mol \cdot dm^{-3} \times 0,5\ dm^{-3} = 0,005\ mol$

Step 3 : ***Find the mass***

$m = n \times M = 0,005\ mol \times 58,45\ g \cdot mol^{-1} = 0,29\ g$

The mass of sodium chloride needed is $0,29$ g

Exercise 19 - 6

1. $5,95$ g of potassium bromide was dissolved in $400\ cm^3$ of water. Calculate its concentration.
2. 100 g of sodium chloride (NaCl) is dissolved in $450\ cm^3$ of water.
   a. How many moles of NaCl are present in solution?
   b. What is the volume of water (in dm^3)?
   c. Calculate the concentration of the solution.
3. What is the molarity of the solution formed by dissolving 80 g of sodium hydroxide (NaOH) in $500\ cm^3$ of water?
4. What mass (g) of hydrogen chloride (HCl) is needed to make up $1000\ cm^3$ of a solution of concentration $1\ mol \cdot dm^{-3}$?
5. How many moles of H_2SO_4 are there in $250\ cm^3$ of a $0,8 mol \cdot dm^{-3}$ sulphuric acid solution? What mass of acid is in this solution?

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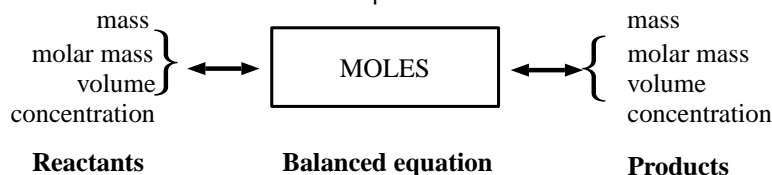
(1.) 0080 (2.) 0081 (3.) 0082 (4.) 0083 (5.) 0084

Stoichiometric calculations

ESAGF

Stoichiometry is the calculation of the quantities of reactants and products in chemical reactions. It is important to know how much product will be formed in a chemical reaction,

or how much of a reactant is needed to make a specific product.

The following diagram shows how the concepts that we have learnt in this chapter relate to each other and to the balanced chemical equation:

See video: VPbxk at www.everythingscience.co.za

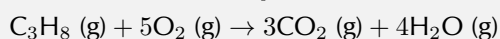
Example 15: *Stoichiometric calculation 1*

QUESTION

What volume of oxygen at S.T.P. is needed for the complete combustion of 2 dm^3 of propane (C_3H_8)? (Hint: CO_2 and H_2O are the products in this reaction (and in all combustion reactions))

SOLUTION

Step 1 : ***Write the balanced equation***

C_3H_8 (g) + 5O_2 (g) → 3CO_2 (g) + 4H_2O (g)

Step 2 : ***Find the ratio***

Because all the reactants are gases, we can use the mole ratios to do a comparison. From the balanced equation, the ratio of oxygen to propane in the reactants is $5 : 1$.

Step 3 : ***Find the answer***

One volume of propane needs five volumes of oxygen, therefore 2 dm^3 of propane will need 10 dm^3 of oxygen for the reaction to proceed to completion.

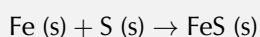
Example 16: *Stoichiometric calculation 2*

QUESTION

What mass of iron (II) sulphide is formed when $5,6$ g of iron is completely reacted with sulphur?

SOLUTION

Step 1 : ***Write the balanced equation***

Fe (s) + S (s) → FeS (s)

Step 2 : ***Calculate the number of moles***

We find the number of moles of the given substance:

$$\text{n} = \frac{\text{m}}{\text{M}} = \frac{5,6\ \text{g}}{55,8\ \text{g} \cdot \text{mol}^{-1}} = 0,1\ \text{mol}$$

Step 3 : ***Find the mole ratio***

We find the mole ratio between what was given and what you are looking for. From the equation 1 mol of Fe gives 1mol of FeS. Therefore, $0,1$ mol of iron in the reactants will give $0,1$ mol of iron sulphide in the product.

Step 4 : ***Find the mass of iron sulphide***

$$m = n \times M = 0,1\ \text{mol} \times 87,9\ \text{g} \cdot\ \text{mol}^{-1} = 8,79\ \text{g}$$

The mass of iron (II) sulphide that is produced during this reaction is $8,79$ g.

Theoretical yield

When we are given a known mass of a reactant and are asked to work out how much product is formed, we are working out the theoretical yield of the reaction. In the laboratory, chemists almost never get this amount of product. In each step of a reaction a small amount

of product and reactants is "lost" either because a reactant did not completely react or some other unwanted products are formed. This amount of product that you actually got is called the actual yield. You can calculate the percentage yield with the following equation:

$$\% \text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100$$

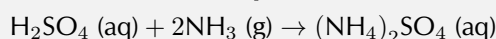
Example 17: *Industrial reaction to produce fertiliser*

QUESTION

Sulphuric acid (H_2SO_4) reacts with ammonia (NH_3) to produce the fertiliser ammonium sulphate ($(NH_4)_2SO_4$). What is the theoretical yield of ammonium sulphate that can be obtained from $2,0$ kg of sulphuric acid? It is found that $2,2$ kg of fertiliser is formed. Calculate the $\%$ yield.

SOLUTION

Step 1 : ***Write the balanced equation***

H_2SO_4 (aq) $+ 2NH_3$ (g) $\rightarrow (NH_4)_2SO_4$ (aq)

Step 2 : ***Calculate the number of moles of the given substance***

$$n(H_2SO_4) = \frac{m}{M} = \frac{2\ 000 \text{ g}}{98,12 \text{ g} \cdot \text{mol}^{-1}} = 20,38320424 \text{ mol}$$

Step 3 : ***Find the mole ratio***

From the balanced equation, the mole ratio of H_2SO_4 in the reactants to $(NH_4)_2SO_4$ in the product is $1:1$. Therefore, $20,383$ mol of H_2SO_4 forms $20,383$ mol of $(NH_4)_2SO_4$.

Step 4 : ***Write the answer***

The maximum mass of ammonium sulphate that can be produced is calculated as follows:

$$m = n \times M = 20,383 \text{ mol} \times 114,04 \text{ g} \cdot \text{mol}^{-1} = 2\ 324,477 \text{ g}$$

The maximum amount of ammonium sulphate that can be produced is $2,324$ kg.

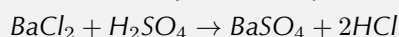
Step 5 : ***Calculate the $\%$ yield***

$$\% \text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100 = \frac{2,2}{2,324} \times 100 = 94,64\%$$

Example 18: *Calculating the mass of reactants and products*

QUESTION

Barium chloride and sulphuric acid react according to the following equation to produce barium sulphate and hydrochloric acid.

$BaCl_2 + H_2SO_4 \rightarrow BaSO_4 + 2HCl$

If you have 2 g of $BaCl_2$:

1. *What quantity (in g) of H_2SO_4 will you need for the reaction so that all the barium chloride is used up?*
2. *What mass of HCl is produced during the reaction?*

SOLUTION

Step 1 : ***Find the number of moles of barium chloride***

$$n = \frac{m}{M} = \frac{2 \text{ g}}{208,2 \text{ g} \cdot \text{mol}^{-1}} = 0,0096 \text{ mol}$$

Step 2 : ***Find the number of moles of sulphuric acid***

According to the balanced equation, 1 mole of $BaCl_2$ will react with 1 mole of H_2SO_4. Therefore, if 0,0096 mol of $BaCl_2$ react, then there must be the same number of moles of H_2SO_4 that react because their mole ratio is 1 : 1.

Step 3 : ***Find the mass of sulphuric acid***

$m = n \times M = 0,0096 \text{ mol} \times 98,12 \text{ g} \cdot \text{mol}^{-1} = 0,94 \text{ g}$

(answer to 1)

Step 4 : ***Find the moles of hydrochloric acid***

According to the balanced equation, 2 moles of HCl are produced for every 1 mole of the two reactants. Therefore the number of moles of

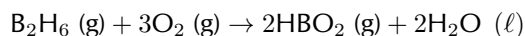
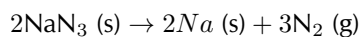
HCl produced is $(2 \times 0,0096$ mol), which equals $0,0192$mol.

Step 5 : ***Find the mass of hydrochloric acid***

m = n × M = $0,0192$ mol × $36,46$ g · mol = $0,7$ g

(answer to 2)

Exercise 19 - 7

1. Diborane, B_2H_6, was once considered for use as a rocket fuel. The combustion reaction for diborane is:
   B_2H_6 (g) + $3O_2$ (g) → $2HBO_2$ (g) + $2H_2O$ (ℓ)
   If we react $2,37$ g of diborane, how many grams of water would we expect to produce?
2. Sodium azide is a commonly used compound in airbags. When triggered, it has the following reaction:
   $2NaN_3$ (s) → $2Na$ (s) + $3N_2$ (g)
   If $23,4$ g of sodium azide is used, how many moles of nitrogen gas would we expect to produce? What volume would this nitrogen gas occupy at STP?
3. Photosynthesis is a chemical reaction that is vital to the existence of life on Earth. During photosynthesis, plants and bacteria convert carbon dioxide gas, liquid water, and light into glucose ($C_6H_{12}O_6$) and oxygen gas.
   a. Write down the equation for the photosynthesis reaction.
   b. Balance the equation.
   c. If 3mol of carbon dioxide are used up in the photosynthesis reaction, what mass of glucose will be produced?

(1.) 0085 (2.) 0086 (3.) 0087

Chapter 19 | Summary

See the summary presentation (Presentation: VPeyf at www.everythingscience.co.za)

- The **mole (n)** (abbreviation mol) is the SI (Standard International) unit for amount of substance.
- The number of particles in a mole is called **Avogadro's number** and its value is $6,022 \times 10^{23}$. These particles could be atoms, molecules or other particle units, depending on the substance.
- The **molar mass (M)** is the mass of one mole of a substance and is measured in grams per mole or $g \cdot mol^{-1}$. The numerical value of an element's molar mass is the same as its relative atomic mass. For a covalent compound, the molar mass has the same numerical value as the molecular mass of that compound. For an ionic substance, the molar mass has the same numerical value as the formula mass of the substance.
- The relationship between moles (n), mass in grams (m) and molar mass (M) is defined by the following equation:

$$n = \frac{m}{M}$$

- In a balanced chemical equation, the number in front of the chemical symbols describes the **mole ratio** of the reactants and products.
- The **empirical formula** of a compound is an expression of the relative number of each type of atom in the compound.
- The **molecular formula** of a compound describes the actual number of atoms of each element in a molecule of the compound.
- The formula of a substance can be used to calculate the **percentage by mass** that each element contributes to the compound.
- The **percentage composition** of a substance can be used to deduce its chemical formula.
- We can use the products of a reaction to determine the formula of one of the reactants.
- We can find the number of moles of waters of crystallisation.
- One mole of gas occupies a volume of $22,4\ dm^3$ at S.T.P..
- The **concentration** of a solution can be calculated using the following equation,

$$C = \frac{n}{V}$$

  where C is the concentration (in $mol \cdot dm^{-3}$), n is the number of moles of solute dissolved in the solution and V is the volume of the solution (in dm^{-3}). The concentration is a measure of the amount of solute that is dissolved in a given volume of liquid.
- The concentration of a solution is measured in $mol \cdot dm^{-3}$.
- **Stoichiometry** is the calculation of the quantities of reactants and products in chemical reactions. It is also the numerical relationship between reactants and products.
- The theoretical yield of a reaction is the maximum amount of product that we expect

to get out of a reaction.

Chapter 19 End of chapter exercises

1. Write only the word/term for each of the following descriptions:
   a. the mass of one mole of a substance
   b. the number of particles in one mole of a substance
2. 5 g of magnesium chloride is formed as the product of a chemical reaction. Select the **true** statement from the answers below:
   a. $0,08$ moles of magnesium chloride are formed in the reaction
   b. the number of atoms of Cl in the product is $0,6022 \times 10^{23}$
   c. the number of atoms of Mg is $0,05$
   d. the atomic ratio of Mg atoms to Cl atoms in the product is $1:1$
3. 2 moles of oxygen gas react with hydrogen. What is the mass of oxygen in the reactants?
   a. 32 g
   b. $0,125$ g
   c. 64 g
   d. $0,063$ g
4. In the compound potassium sulphate (K_2SO_4), oxygen makes up $x\%$ of the mass of the compound. x = ?
   a. $36,8$
   b. $9,2$
   c. 4
   d. $18,3$
5. The concentration of a 150 cm^3 solution, containing 5 g of NaCl is:
   a. $0,09$ mol · dm^{-3}
   b. $5,7 \times 10^{-4}$ mol · dm^{-3}
   c. $0,57$ mol · dm^{-3}
   d. $0,03$ mol · dm^{-3}
6. Calculate the number of moles in:
   a. 5 g of methane (CH_4)
   b. $3,4$ g of hydrochloric acid
   c. 6,2 g of potassium permanganate ($KMnO_4$)
   d. 4 g of neon
   e. $9,6$ kg of titanium tetrachloride ($TiCl_4$)
7. Calculate the mass of:
   a. $0,2$ mol of potassium hydroxide (KOH)
   b. $0,47$ mol of nitrogen dioxide

c. $5,2$ mol of helium

d. $0,05$ mol of copper (II) chloride ($CuCl_2$)

e. $31,31 \times 10^{23}$ molecules of carbon monoxide (CO)

8. Calculate the percentage that each element contributes to the overall mass of:

   a. Chloro-benzene (C_6H_5Cl)

   b. Lithium hydroxide (LiOH)

9. CFC's (chlorofluorocarbons) are one of the gases that contribute to the depletion of the ozone layer. A chemist analysed a CFC and found that it contained $58,64\%$ chlorine, $31,43\%$ fluorine and $9,93\%$ carbon. What is the empirical formula?

10. 14 g of nitrogen combines with oxygen to form 46 g of a nitrogen oxide. Use this information to work out the formula of the oxide.

11. Iodine can exist as one of three oxides (I_2O_4 ; I_2O_5 ; I_4O_9). A chemist has produced one of these oxides and wishes to know which one they have. If he started with 508 g of iodine and formed 652 g of the oxide, which oxide has he produced?

12. A fluorinated hydrocarbon (a hydrocarbon is a chemical compound containing hydrogen and carbon) was analysed and found to contain $8,57\%$ H, $51,05\%$ C and $40,38\%$ F.

    a. What is its empirical formula?

    b. What is the molecular formula if the molar mass is $94,1$ g $\cdot$ mol^{-1}?

13. Copper sulphate crystals often include water. A chemist is trying to determine the number of moles of water in the copper sulphate crystals. She weighs out 3 g of copper sulphate and heats this. After heating, she finds that the mass is $1,9$ g. What is the number of moles of water in the crystals? (Copper sulphate is represented by $CuSO_4 \cdot xH_2O$).

14. 300 cm^3 of a $0,1$ mol$\cdot$dm^{-3} solution of sulphuric acid is added to 200 cm^3 of a $0,5$ mol $\cdot$ dm^{-3} solution of sodium hydroxide.

    a. Write down a balanced equation for the reaction which takes place when these two solutions are mixed.

    b. Calculate the number of moles of sulphuric acid which were added to the sodium hydroxide solution.

    c. Is the number of moles of sulphuric acid enough to fully neutralise the sodium hydroxide solution? Support your answer by showing all relevant calculations.

15. A learner is asked to make 200 cm^3 of sodium hydroxide (NaOH) solution of concentration $0,5$ mol $\cdot$ dm^{-3}.

    a. Determine the mass of sodium hydroxide pellets he needs to use to do this.

    b. Using an accurate balance the learner accurately measures the correct mass of the NaOH pellets. To the pellets he now adds exactly 200 cm^3 of pure water. Will his solution have the correct concentration? Explain your answer.

c. The learner then takes $300\,\text{cm}^3$ of a $0,1\ \text{mol}\cdot\text{dm}^{-3}$ solution of sulphuric acid (H_2SO_4) and adds it to $200\ \text{cm}^3$ of a $0,5\ \text{mol}\cdot\text{dm}^{-3}$ solution of NaOH at 25^0C.
   d. Write down a balanced equation for the reaction which takes place when these two solutions are mixed.
   e. Calculate the number of moles of H_2SO_4 which were added to the NaOH solution.

16. $96,2$ g sulphur reacts with an unknown quantity of zinc according to the following equation: $Zn + S \rightarrow ZnS$
   a. What mass of zinc will you need for the reaction, if all the sulphur is to be used up?
   b. Calculate the theoretical yield for this reaction.
   c. It is found that 275 g of zinc sulphide was produced. Calculate the % yield.

17. Calcium chloride reacts with carbonic acid to produce calcium carbonate and hydrochloric acid according to the following equation:
$CaCl_2 + H_2CO_3 \rightarrow CaCO_3 + 2HCl$
If you want to produce 10 g of calcium carbonate through this chemical reaction, what quantity (in g) of calcium chloride will you need at the start of the reaction?

More practice video solutions or help at www.everythingscience.co.za

(1.) 0088 (2.) 0089 (3.) 008a (4.) 008b (5.) 008c (6.) 008d
(7.) 008e (8.) 008f (9.) 008g (10.) 008h (11.) 008i (12.) 008j
(13.) 008k (14.) 008m (15.) 008n (16.) 008p (17.) 008q

Vectors and scalars 20

Introduction to vectors and scalars

We come into contact with many physical quantities in the natural world on a daily basis. For example, things like time, mass, weight, force, and electric charge, are physical quantities with which we are all familiar. We know that time passes and physical objects have mass. Things have weight due to gravity. We exert forces when we open doors, walk along the street and kick balls. We experience electric charge directly through static shocks in winter and through using anything which runs on electricity.

There are many physical quantities in nature, and we can divide them up into two broad groups called **vectors** and **scalars**. See introductory video: (Video: VPgao at www.everythingscience.c

Scalars and vectors ESAGI

Scalars are physical quantities which have only a number value or a size (magnitude). A scalar tells you **how much** of something there is.

> *DEFINITION: Scalar*
>
> A scalar is a physical quantity that has only a magnitude (size).

For example, a person buys a tub of margarine which is labelled with a mass of 500 g. The mass of the tub of margarine is a scalar quantity. It only needs one number to describe it, in this case, 500 g.

Vectors are different because they are physical quantities which have a size *and* a direction. A vector tells you **how much** of something there is *and* **which direction** it is in.

DEFINITION: Vector

A vector is a physical quantity that has both a *magnitude* and a *direction*.

For example, a car is travelling east along a freeway at $100\,\text{km}\cdot\text{h}^{-1}$. What we have here is a vector called the velocity. The car is moving at $100\,\text{km}\cdot\text{h}^{-1}$ (this is the magnitude) and we know where it is going – east (this is the direction). These two quantities, the speed *and* direction of the car, (a magnitude and a direction) together form a vector we call velocity.

Examples of scalar quantities:

- **mass** has only a value, no direction
- **electric charge** has only a value, no direction

Examples of vector quantities:

- **force** has a value and a direction. You push or pull something with some strength (magnitude) in a particular direction
- **weight** has a value and a direction. Your weight is proportional to your mass (magnitude) and is always in the direction towards the centre of the earth.

Exercise 20 - 1

Classify the following as vectors or scalars

1. length
2. force
3. direction
4. height
5. time
6. speed
7. temperature

(1.-7.) 008r

Vector notation

ESAGJ

Vectors are different to scalars and must have their own notation. There are many ways of writing the symbol for a vector. In this book vectors will be shown by symbols with an arrow pointing to the right above it. For example, $\vec{F}$, $\vec{W}$ and $\vec{v}$ represent the *vectors* of force, weight and velocity, meaning they have both a magnitude *and* a direction.

Sometimes just the magnitude of a vector is needed. In this case, the arrow is omitted. For the case of the force vector:

- $\vec{F}$ represents the force vector
- F represents the magnitude of the force vector

Graphical representation of vectors

ESAGK

Vectors are drawn as arrows. An arrow has both a magnitude (how long it is) and a direction (the direction in which it points). The starting point of a vector is known as the *tail* and the end point is known as the *head*.

See video: VPgdw at www.everythingscience.co.za

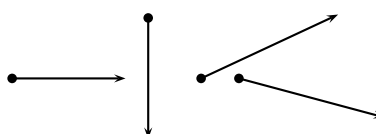



Figure 20.2: Examples of vectors

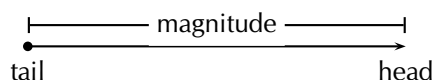



Figure 20.3: Parts of a vector

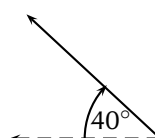
Directions

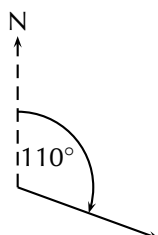
There are many acceptable methods of writing vectors. As long as the vector has a magnitude and a direction, it is most likely acceptable. These different methods come from the different methods of representing a direction for a vector.

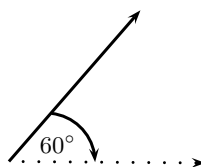
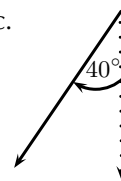
Relative Directions

The simplest way to show direction is with relative directions: to the left, to the right, forward, backward, up and down.

Compass Directions

Another common method of expressing directions is to use the points of a compass: North, South, East, and West. If a vector does not point exactly in one of the compass directions, then we use an angle. For example, we can have a vector pointing $40°$ North of West. Start with the vector pointing along the West direction (look at the dashed arrow below), then rotate the vector towards the north until there is a $40°$ angle between the vector and the West direction (the solid arrow below). The direction of this vector can also be described as: W $40°$ N (West $40°$ North); or N $50°$ W (North $50°$ West).

Bearing

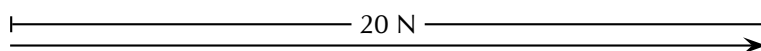
A further method of expressing direction is to use a *bearing*. A bearing is a direction relative to a fixed point. Given just an angle, the convention is to define the angle clockwise with respect to North. So, a vector with a direction of $110°$ has been rotated clockwise $110°$ relative to North. A bearing is always written as a three digit number, for example $275°$ or $080°$ (for $80°$).

Exercise 20 - 2

1. Classify the following quantities as scalars or vectors:
   a. 12 km
   b. 1 m south
   c. $2\,\text{m} \cdot \text{s}^{-1}$, $45°$
   d. $075°$, 2 cm
   e. $100\,\text{k} \cdot \text{h}^{-1}$, $0°$
2. Use two different notations to write down the direction of the vector in each of the following diagrams:

More practice video solutions or help at www.everythingscience.co.za

(1.) 008s (2.) 008t

Drawing Vectors

ESAGM

In order to draw a vector accurately we must represent its magnitude properly and include a reference direction in the diagram. A scale allows us to translate the length of the arrow into the vector's magnitude. For instance if one chooses a scale of 1 cm = 2 N (1 cm represents 2 N), a force of 20 N towards the East would be represented as an arrow 10 cm long pointing towards the right. The points of a compass are often used to show direction or alternatively an arrow pointing in the reference direction.

Method: Drawing Vectors

1. Decide upon a scale and write it down.

2. Decide on a reference direction
3. Determine the length of the arrow representing the vector, by using the scale.
4. Draw the vector as an arrow. Make sure that you fill in the arrow head.
5. Fill in the magnitude of the vector.

Example 1: *Drawing vectors I*

QUESTION

Draw the following vector quantity: $\vec{v} = 6\ m \cdot s^{-1}$ *North*

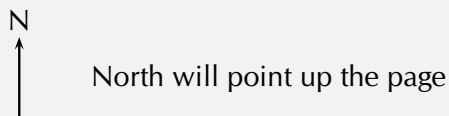
SOLUTION

Step 1 : ***Decide on a scale and write it down.***

$1\ \text{cm} = 2\ \text{m} \cdot \text{s}^{-1}$

Step 2 : ***Decide on a reference direction***

N

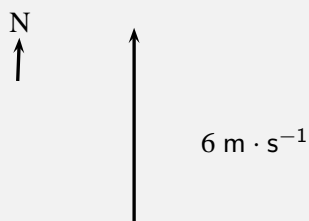
North will point up the page

Step 3 : ***Determine the length of the arrow at the specific scale.***

If $1\ \text{cm} = 2\ \text{m} \cdot \text{s}^{-1}$, then $6\ \text{m} \cdot \text{s}^{-1} = 3\ \text{cm}$

Step 4 : ***Draw the vector as an arrow.***

Scale used: $1\ \text{cm} = 2\ \text{m} \cdot \text{s}^{-1}$

N

$6\ \text{m} \cdot \text{s}^{-1}$

Example 2: *Drawing vectors 2*

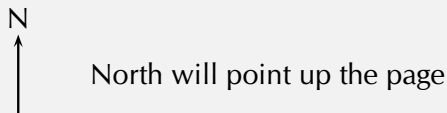
QUESTION

Draw the following vector quantity: $\vec{s}$ = 16 m east

SOLUTION

Step 1 : ***Decide on a scale and write it down.***

1 cm = 4 m

Step 2 : ***Decide on a reference direction***

Step 3 : ***Determine the length of the arrow at the specific scale.***

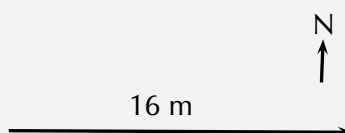
If 1 cm = 4 m, then 16 m = 4 cm

Step 4 : ***Draw the vector as an arrow***

Scale used: 1 cm = 4 m

Direction = East

N

16 m

Exercise 20 - 3

Draw each of the following vectors to scale. Indicate the scale that you have used:

1. 12 km south
2. 1,5 m N $45°$ W
3. 1 m · s^{-1}, $20°$ East of North
4. 50 km · h^{-1}, $085°$
5. 5 mm, $225°$

More practice video solutions or help at www.everythingscience.co.za

(1.-5.) 008u

Properties of vectors

ESAGN

Vectors are mathematical objects and we will now study some of their mathematical properties.

If two vectors have the same magnitude (size) *and* the same direction, then we call them equal to each other. For example, if we have two forces, $\vec{F_1} = 20$ N *in the upward direction* and $\vec{F_2} = 20$ N *in the upward direction*, then we can say that $\vec{F_1} = \vec{F_2}$.

DEFINITION: Equality of vectors

Two vectors are equal if they have the **same** magnitude and the **same** direction.

Just like scalars which can have positive or negative values, vectors can also be positive or negative. A negative vector is a vector which points in the direction *opposite* to the **reference positive direction**. For example, if in a particular situation, we define the upward direction as the reference positive direction, then a force $\vec{F_1} = 30$ N *downwards* would be a *negative vector* and could also be written as $\vec{F_1} = -30$ N. In this case, the negative (-) sign indicates that the direction of $\vec{F_1}$ is opposite to that of the reference positive direction.

DEFINITION: Negative vector

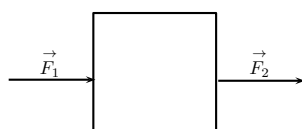
A negative vector is a vector that has the *opposite* direction to the reference positive direction.

Like scalars, vectors can also be added and subtracted. We will investigate how to do this next.

Addition and subtraction of vectors

Adding vectors

When vectors are added, we need to take into account *both* their magnitudes *and* directions. See video: VPgel at www.everythingscience.co.za

For example, imagine the following. You and a friend are trying to move a heavy box. You stand behind it and push forwards with a force $\vec{F_1}$ and your friend stands in front and pulls it towards them with a force $\vec{F_2}$. The two forces are in the *same* direction (i.e. forwards) and so the total force acting on the box is:

It is very easy to understand the concept of vector addition through an activity using the **displacement** vector.
Displacement is the vector which describes the change in an object's position. It is a vector that points from the initial position to the final position.

Activity:	*Adding vectors*

Materials: masking tape

Method:

Tape a line of masking tape horizontally across the floor. This will be your starting point.

Task 1:

Take 2 steps in the forward direction. Use a piece of masking tape to mark your end point and label it **A**. Then take another 3 steps in the forward direction. Use masking tape to mark your final position as **B**. Make sure you try to keep your steps all the same length!

Task 2:

Go back to your starting line. Now take 3 steps forward. Use a piece of masking tape to mark your end point and label it **B**. Then take another 2 steps forward and use a new piece of masking tape to mark your final position as **A**.

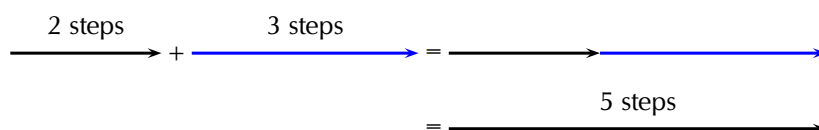
Discussion:

What do you notice?

1. In *Task 1*, the first 2 steps forward represent a displacement vector and the second 3 steps forward also form a displacement vector. If we did not stop after the first 2 steps, we would have taken 5 steps in the forward direction in

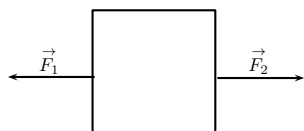
total. Therefore, if we add the displacement vectors for 2 steps and 3 steps, we should get a total of 5 steps in the forward direction.

2. It does not matter whether you take 3 steps forward and then 2 steps forward, or two steps followed by another 3 steps forward. Your final position is the same! The order of the addition does not matter!

We can represent vector addition graphically, based on the activity above. Draw the vector for the first two steps forward, followed by the vector with the next three steps forward.

We add the second vector at the end of the first vector, since this is where we now are after the first vector has acted. The vector from the tail of the first vector (the starting point) to the head of the second vector (the end point) is then the sum of the vectors.

As you can convince yourself, the order in which you add vectors does not matter. In the example above, if you decided to first go 3 steps forward and then another 2 steps forward, the end result would still be 5 steps forward.

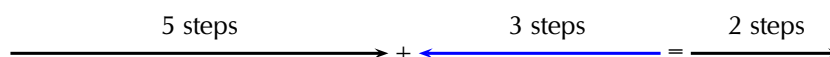
Subtracting vectors

Let's go back to the problem of the heavy box that you and your friend are trying to move. If you didn't communicate properly first, you both might think that you should pull in your own directions! Imagine you stand behind the box and pull it towards you with a force $\vec{F_1}$ and your friend stands at the front of the box and pulls it towards them with a force $\vec{F_2}$. In this case the two forces are in *opposite* directions. If we define the direction your friend is pulling in as *positive* then the force you are exerting must be *negative* since it is in the opposite direction. We can write the total force exerted on the box as the sum of the individual forces:

$\vec{F_1}$ $\vec{F_2}$

$$\begin{aligned} \vec{F_{Tot}} &= \vec{F_2} + (-\vec{F_1}) \\ &= \vec{F_2} - \vec{F_1} \end{aligned}$$

What you have done here is actually to subtract two vectors! This is the same as adding two vectors which have opposite directions.

As we did before, we can illustrate vector subtraction nicely using displacement vectors. If you take 5 steps forward and then subtract 3 steps forward you are left with only two steps forward:

What did you physically do to subtract 3 steps? You originally took 5 steps forward but then you took 3 steps *backward* to land up back with only 2 steps forward. That backward displacement is represented by an arrow pointing to the left (backwards) with length 3. The net result of adding these two vectors is 2 steps forward:

Tip

Subtracting a vector from another is the same as adding a vector in the opposite direction.

Thus, subtracting a vector from another is the same as adding a vector in the opposite direction (i.e. subtracting 3 steps forwards is the same as adding 3 steps backwards).

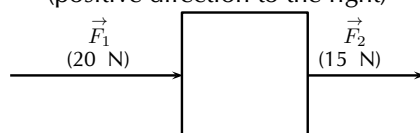
The resultant vector

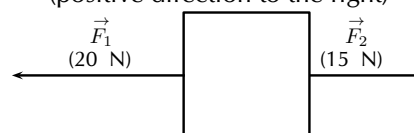
The final quantity you get when adding or subtracting vectors is called the **resultant vector**. In other words, the individual vectors can be replaced by the resultant – the overall effect is the same. See video: VPgem at www.everythingscience.co.za

DEFINITION: Resultant vector

The resultant vector is the single vector whose effect is the same as the individual vectors acting together.

We can illustrate the concept of the resultant vector by considering our two situations in using forces to move the heavy box. In the first case (on the left), you and your friend are applying forces in the same direction. The resultant force will be the sum of your two applied forces in that direction. In the second case (on the right), the forces are applied in opposite directions. The resultant vector will again be the sum of your two applied forces, however after choosing a positive direction, one force will be positive and the other will be negative and the sign of the resultant force will just depend on which direction you chose as positive. For clarity look at the diagrams below.

Forces are applied in the same direction
(positive direction to the right)

$$\begin{aligned}\vec{F_R} &= \vec{F_1} + \vec{F_2} \\ &= 20\text{ N} + 15\text{ N} \\ &= 35\text{ N } \textit{to the right}\end{aligned}$$

Forces are applied in opposite directions
(positive direction to the right)

$$\begin{aligned}\vec{F_R} &= \vec{F_2} + (-\vec{F_2}) \\ &= \vec{F_2} - \vec{F_1} \\ &= 15\text{ N} - 20\text{ N} \\ &= -5\text{ N} \\ &= 5\text{ N } \textit{to the left}\end{aligned}$$

There is a special name for the vector which has the same magnitude as the resultant vector but the *opposite* direction: the **equilibrant**. If you add the resultant vector and the equilibrant vectors together, the answer is always zero because the equilibrant cancels the resultant out.

DEFINITION: Equilibrant

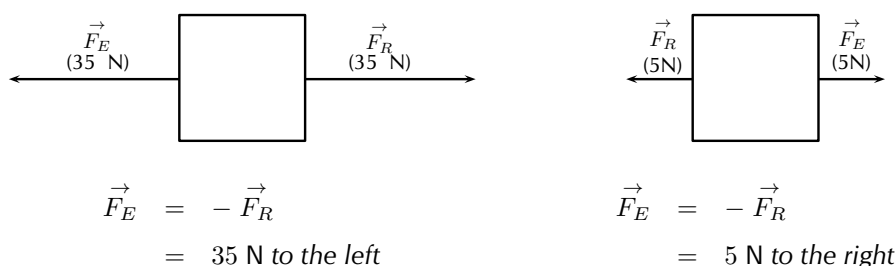
The equilibrant is the vector which has the *same magnitude* but *opposite direction* to the resultant vector.

If you refer to the pictures of the heavy box before, the equilibrant forces for the two situations would look like:

$$\begin{aligned}\vec{F}_E &= -\vec{F}_R \\ &= 35\text{ N } \textit{to the left}\end{aligned}$$

$$\begin{aligned}\vec{F}_E &= -\vec{F}_R \\ &= 5\text{ N } \textit{to the right}\end{aligned}$$

Techniques of vector addition

 ESAGP

Now that you have learned about the mathematical properties of vectors, we return to vector addition in more detail. There are a number of techniques of vector addition. These techniques fall into two main categories - graphical and algebraic techniques.

Graphical techniques

 ESAGQ

Graphical techniques involve drawing accurate scale diagrams to denote individual vectors and their resultants. We will look at just one graphical method: the head-to-tail method.

Method: Head-to-Tail Method of Vector Addition

1. Draw a rough sketch of the situation.
2. Choose a scale and include a reference direction.
3. Choose any of the vectors and draw it as an arrow in the correct direction and of the correct length – remember to put an arrowhead on the end to denote its direction.
4. Take the next vector and draw it as an arrow starting from the arrowhead of the first vector in the correct direction and of the correct length.
5. Continue until you have drawn each vector – each time starting from the head of the previous vector. In this way, the vectors to be added are drawn one after the other head-to-tail.
6. The resultant is then the vector drawn from the tail of the first vector to the head of the last. Its magnitude can be determined from the length of its arrow using the scale. Its direction too can be determined from the scale diagram.

Let's consider some more examples of vector addition using displacements. The arrows tell you how far to move and in what direction. Arrows to the right correspond to steps forward, while arrows to the left correspond to steps backward. Look at all of the examples below and check them.

This example says 1 step forward and then another step forward is the same as an arrow twice as long – two steps forward.

1 step + 1 step = 2 steps = 2 steps

This example says 1 step backward and then another step backward is the same as an arrow twice as long – two steps backward.

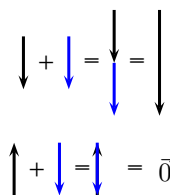
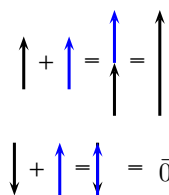
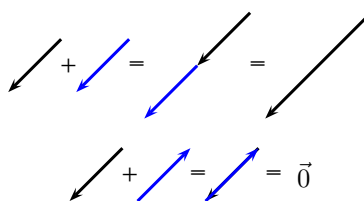
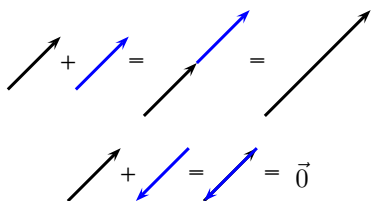
1 step + 1 step = 2 steps = 2 steps

It is sometimes possible that you end up back where you started. In this case the net result of what you have done is that you have gone nowhere (your start and end points are at the same place). In this case, your resultant displacement is a vector with length zero units. We use the symbol $\vec{0}$ to denote such a vector:

1 step + 1 step = 1 step 1 step $= \vec{0}$

1 step + 1 step = 1 step 1 step $= \vec{0}$

Check the following examples in the same way. Arrows up the page can be seen as steps left and arrows down the page as steps right.

Try a couple to convince yourself!

It is important to realise that the directions are not special– 'forward and backwards' or 'left and right' are treated in the same way. The same is true of any set of parallel directions:

In the above examples the separate displacements were parallel to one another. However the same head-to-tail technique of vector addition can be applied to vectors in any direction.

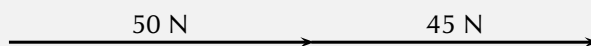
Example 3: *Head-to-tail addition 1*

QUESTION

A car breaks down in the road and you and your friend, who happen to be walking past, help the driver push-start it. You and your friend stand together at the rear of the car. If you push with a force of 50 N and your friend pushes with a force of 45 N, what is the resultant force on the car? Use the head-to-tail technique to calculate the answer graphically.

SOLUTION

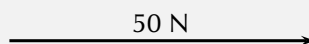
Step 1 : ***Draw a rough sketch of the situation***

50 N 45 N

Step 2 : ***Choose a scale and a reference direction***

Let's choose the direction *to the right* as the positive direction. The scale can be 1 cm = 10 N.

Step 3 : ***Choose one of the vectors and draw it as an arrow of the correct***

length in the correct direction

Start with your force vector and draw an arrow pointing to the right which is 5 cm long (i.e. 50 N = 5×10 N, therefore, you must multiply your cm scale by 5 as well).

Step 4 : ***Take the next vector and draw it starting at the arrowhead of the previous vector.***

Since your friend is pushing in the same direction as you, your force vectors must point in the same direction. Using the scale, this arrow should be 4,5 cm long.

Step 5 : ***Draw the resultant, measure its length and find its direction***

There are only two vectors in this problem, so the resultant vector must be drawn from the tail (i.e. starting point) of the first vector to the head of the second vector.

50 N + 45 N = 95 N

The resultant vector measures 9,5 cm and points to the right. Therefore the resultant force must be 95 N in the positive direction (*or* to the right).

Example 4: *Head-to-tail addition 2*

QUESTION

Use the graphical head-to-tail method to determine the resultant force on a rugby player if two players on his team are pushing him forwards with forces of $\overrightarrow{F_1}$ = *60 N and* $\overrightarrow{F_2}$ = *90 N respectively and two players from the opposing team are pushing him backwards with forces of* $\overrightarrow{F_3}$ = *100 N and* $\overrightarrow{F_4}$ = *65 N respectively.*

SOLUTION

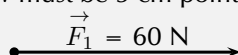
Step 1 : ***Choose a scale and a reference direction***

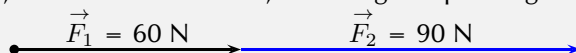
Let's choose a scale of 0,5 cm = 10 N and for our diagram we will

define the positive direction as *to the right*.

Step 2 : ***Choose one of the vectors and draw it as an arrow of the correct length in the correct direction***

We will start with drawing the vector $\vec{F_1} = 60$ N, pointing in the positive direction. Using our scale of 0,5 cm = 10 N, the length of the arrow must be 3 cm pointing to the right.

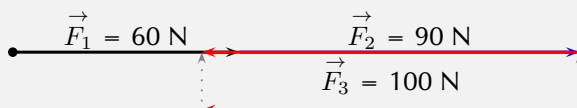
$\vec{F_1} = 60$ N

Step 3 : ***Take the next vector and draw it starting at the arrowhead of the previous vector***

The next vector is $\vec{F_2} = 90$ N in the same direction as $\vec{F_1}$. Using the scale, the arrow should be 4,5 cm long and pointing to the right.

$\vec{F_1} = 60$ N $\vec{F_2} = 90$ N

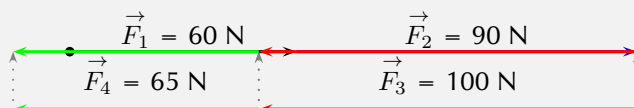
Step 4 : ***Take the next vector and draw it starting at the arrowhead of the previous vector***

The next vector is $\vec{F_3} = 100$ N in the *opposite* direction. Using the scale, this arrow should be 5 cm long and point to the *left*.

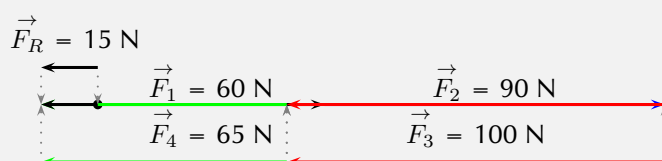
Note: We are working in one dimension so this arrow would be drawn on top of the first vectors to the left. This will get messy so we'll draw it next to the actual line as well to show you what it looks like.

$\vec{F_1} = 60$ N $\vec{F_2} = 90$ N
$\vec{F_3} = 100$ N

Step 5 : ***Take the next vector and draw it starting at the arrowhead of the previous vector***

The fourth vector is $\vec{F_4} = 65$ N also in the opposite direction. Using the scale, this arrow must be 3,25 cm long and point to the left.

$\vec{F_1} = 60$ N $\vec{F_2} = 90$ N
$\vec{F_4} = 65$ N $\vec{F_3} = 100$ N

Step 6 : ***Draw the resultant, measure its length and find its direction***

We have now drawn all the force vectors that are being applied to the player. The resultant vector is the arrow which starts at the tail of the first vector and ends at the head of the last drawn vector.

$\vec{F_R} = 15$ N
$\vec{F_1} = 60$ N $\vec{F_2} = 90$ N
$\vec{F_4} = 65$ N $\vec{F_3} = 100$ N

The resultant vector measures 0,75 cm which, using our scale is equivalent to 15 N and points to the left (*or* the negative direction *or* the direction the opposing team members are pushing in).

Algebraic techniques

Vectors in a Straight Line

Whenever you are faced with adding vectors acting in a straight line (i.e. some directed left and some right, or some acting up and others down) you can use a very simple algebraic technique:

Method: Addition/Subtraction of Vectors in a Straight Line

1. Choose a positive direction. As an example, for situations involving displacements in the directions west and east, you might choose west as your positive direction. In that case, displacements east are negative.
2. Next simply add (or subtract) the magnitude of the vectors using the appropriate signs.
3. As a final step the direction of the resultant should be included in words (positive answers are in the positive direction, while negative resultants are in the negative direction).

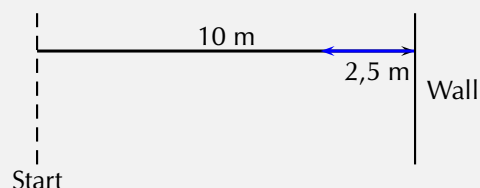
Let us consider a few examples.

Example 5: *Adding vectors algebraically I*

QUESTION

A tennis ball is rolled towards a wall which is 10 m away from the ball. If after striking the wall the ball rolls a further 2,5 m along the ground away from the wall, calculate algebraically the ball's resultant displacement.

SOLUTION

Step 1 : ***Draw a rough sketch of the situation***

Step 2 : ***Decide which method to use to calculate the resultant***

We know that the resultant displacement of the ball ($\vec{x}_R$) is equal to the sum of the ball's separate displacements ($\vec{x}_1$ and $\vec{x}_2$):

$$\vec{x}_R = \vec{x}_1 + \vec{x}_2$$

Since the motion of the ball is in a straight line (i.e. the ball moves towards and away from the wall), we can use the method of algebraic addition just explained.

Step 3 : ***Choose a positive direction***

Let's choose the **positive** direction to be towards the wall. This means that the **negative** direction is away from the wall.

Step 4 : ***Now define our vectors algebraically***

With right positive:

$$\begin{aligned} \vec{x}_1 &= +10,0\,\mathrm{m} \\ \vec{x}_2 &= -2,5\,\mathrm{m} \end{aligned}$$

Step 5 : ***Add the vectors***

Next we simply add the two displacements to give the resultant:

$$\begin{aligned} \vec{x}_R &= (+10\,\mathrm{m}) + (-2,5\,\mathrm{m}) \\ &= (+7,5)\,\mathrm{m} \end{aligned}$$

Step 6 : ***Quote the resultant***

Finally, in this case towards the wall is the positive direction, so: $\vec{x}_R$ = 7,5 m towards the wall.

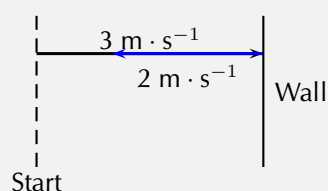
Example 6: *Subtracting vectors algebraically I*

QUESTION

Suppose that a tennis ball is thrown horizontally towards a wall at an initial velocity of 3 $m \cdot s^{-1}$to the right. After striking the wall, the ball returns to the thrower at 2 $m \cdot s^{-1}$. Determine the change in velocity of the ball.

SOLUTION

Step 1 : ***Draw a sketch***

A quick sketch will help us understand the problem.

Step 2 : ***Decide which method to use to calculate the resultant***

Remember that velocity is a vector. The change in the velocity of the ball is equal to the difference between the ball's initial and final velocities:

$$\Delta\vec{v} = \vec{v}_f - \vec{v}_i$$

Since the ball moves along a straight line (i.e. left and right), we can use the algebraic technique of vector subtraction just discussed.

Step 3 : ***Choose a positive direction***

Choose the **positive** direction to be towards the wall. This means that the **negative** direction is away from the wall.

Step 4 : ***Now define our vectors algebraically***

$$\begin{aligned} \vec{v}_i &= +3\,\mathrm{m \cdot s^{-1}} \\ \vec{v}_f &= -2\,\mathrm{m \cdot s^{-1}} \end{aligned}$$

Step 5 : ***Subtract the vectors***

Thus, the change in velocity of the ball is:

$$\begin{aligned}\Delta\vec{v} &= (-2\,\text{m}\cdot\text{s}^{-1}) - (+3\,\text{m}\cdot\text{s}^{-1}) \\ &= (-5)\,\text{m}\cdot\text{s}^{-1}\end{aligned}$$

Step 6 : ***Quote the resultant***

Remember that in this case towards the wall means a positive velocity, so away from the wall means a negative velocity: $\Delta\vec{v} = 5\,\text{m}\cdot\text{s}^{-1}$ away from the wall.

Example 7: *Adding vectors algebraically II*

QUESTION

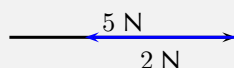
A man applies a force of 5 *N on a crate. The crate pushes back on the man with a force of* 2 *N. Calculate algebraically the resultant force that the man applies to the crate.*

SOLUTION

Step 1 : ***Draw a sketch***

A quick sketch will help us understand the problem.

5 N

2 N

Step 2 : ***Decide which method to use to calculate the resultant***

Remember that force is a vector. Since the crate moves along a straight line (i.e. left and right), we can use the algebraic technique of vector addition just discussed.

Step 3 : ***Choose a positive direction***

Choose the **positive** direction to be towards the crate (i.e. in the same direction that the man is pushing). This means that the **negative** direction is away from the crate (i.e. against the direction that the man is pushing).

Step 4 : ***Now define our vectors algebraically***

$$\vec{F}_{\text{man}} = +5 \text{ N}$$
$$\vec{F}_{\text{crate}} = -2 \text{ N}$$

Step 5 : ***Subtract the vectors***

Thus, the resultant force is:

$$\vec{F}_{\text{man}} + \vec{F}_{\text{crate}} = (5 \text{ N}) + (2 \text{ N}) = 7 \text{ N}$$

Step 6 : ***Quote the resultant***

Remember that in this case towards the crate means a positive force: 7 N towards the crate.

Remember that the technique of addition and subtraction just discussed can only be applied to vectors acting along a straight line. When vectors are not in a straight line, i.e. at an angle to each other then simple geometric and trigonometric techniques can be used to find resultant vectors.

Exercise 20 - 4

1. Harold walks to school by walking 600 m Northeast and then 500 m N 40° W. Determine his resultant displacement by using accurate scale drawings.
2. A dove flies from her nest, looking for food for her chick. She flies at a velocity of 2 $\text{m} \cdot \text{s}^{-1}$on a bearing of 135° and then at a velocity of 1,2 $\text{m} \cdot \text{s}^{-1}$on a bearing of 230°. Calculate her resultant velocity by using accurate scale drawings.
3. A squash ball is dropped to the floor with an initial velocity of 2,5 $\text{m} \cdot \text{s}^{-1}$. It rebounds (comes back up) with a velocity of 0,5 $\text{m} \cdot \text{s}^{-1}$.
   (a) What is the change in velocity of the squash ball?
   (b) What is the resultant velocity of the squash ball?
4. A frog is trying to cross a river. It swims at 3 $\text{m} \cdot \text{s}^{-1}$in a northerly direction towards the opposite bank. The water is flowing in a westerly direction at 5 $\text{m} \cdot \text{s}^{-1}$. Find the frog's resultant velocity by using appropriate calculations. Include a rough sketch of the situation in your answer.

5. Mpihlonhle walks to the shop by walking 500 m Northwest and then 400 m N 30° E. Determine her resultant displacement by doing appropriate calculations.

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(1.) 008v (2.) 008w (3.) 008x (4.) 008y (5.) 008z

Chapter 20 | Summary

See the summary presentation (Presentation: VPgig at www.everythingscience.co.za)

- A scalar is a physical quantity with magnitude only.
- A vector is a physical quantity with magnitude and direction.
- Vectors may be represented as arrows where the length of the arrow indicates the magnitude and the arrowhead indicates the direction of the vector.
- The direction of a vector can be indicated by referring to another vector or a fixed point (e.g. $30°$ from the river bank); using a compass (e.g. N $30°$ W); or bearing (e.g. $053°$).
- The resultant vector is the single vector whose effect is the same as the individual vectors acting together.

Chapter 20 End of chapter exercises

1. A point is acted on by two forces in equilibrium. The forces
   a. have equal magnitudes and directions.
   b. have equal magnitudes but opposite directions.
   c. act perpendicular to each other.
   d. act in the same direction.

2. Which of the following contains two vectors and a scalar?
    a. distance, acceleration, speed
    b. displacement, velocity, acceleration
    c. distance, mass, speed
    d. displacement, speed, velocity
3. Two vectors act on the same point. What should the angle between them be so that a maximum resultant is obtained?
    a. $0°$
    b. $90°$
    c. $180°$
    d. cannot tell
4. Two forces, 4 N and 11 N, act on a point. Which one of the following cannot be the magnitude of a resultant?
    a. 4 N
    b. 7 N
    c. 11 N
    d. 15 N

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(1.) 0092 (2.) 0094 (3.) 0095 (4.) 0096

Motion in one dimension

21

Introduction

ESAGS

This chapter is about how things move along a straight line or, more scientifically, how things move *in one dimension*. This is useful for learning how to describe the movement (motion) of cars along a straight road or of trains along straight railway tracks. There are three features of motion that we use to describe exactly how an object moves. They are:

Traffic often moves along a straight line.

Photograph by warrenski on Flickr.com

FACT

The **jerk** is the name we give to how fast the acceleration is changing.

1. **position** which tells us about an object's location or **displacement** which tells us about change of location
2. **speed** which tells us how fast the object is moving or **velocity** which tells us how fast the object is moving and where it is moving to, and
3. **acceleration** which tells us exactly how fast the object's speed and velocity are changing.

See introductory video: (Video: VPgiq at www.everythingscience.co.za)

Reference frame

ESAGT

The first thing to focus on when studying motion of an object or person is their position. The word *position* describes your location (where you are). However, saying that you are *here* or *there* is meaningless, you have to use known points (reference points) to help specify your position.

For example, if you were in a classroom and wanted to tell a classmate where you were standing you would first give them a reference point. The reference point might be the classroom door. You would then be able to say that you are 2 m from the doorway. This still doesn't give your position precisely. We need to provide a reference point and a coordinate system to use to define the location precisely.

Describing your location

Photograph by chokola on Flickr.com

Then you can say that you are, for example, 2 m from the door directly inside the classroom. The classroom door is a reference point and inside/outside is the coordinate system you have chosen. A frame of reference or **reference frame** is reference point which serves as the origin for a coordinate system. The coordinate system can be up or down, inside or outside, left or right or even forward or backward. These are all examples that define a 1-dimensional coordinate system. We choose one of the directions as the **positive** direction.

DEFINITION: Frame of reference

A frame of reference is a reference point combined with a set of directions.

A graphical representation of a 1-dimensional frame of reference:

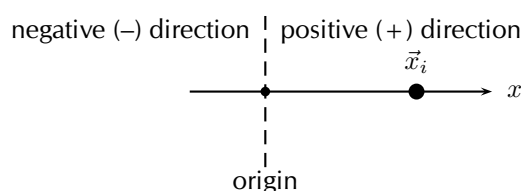
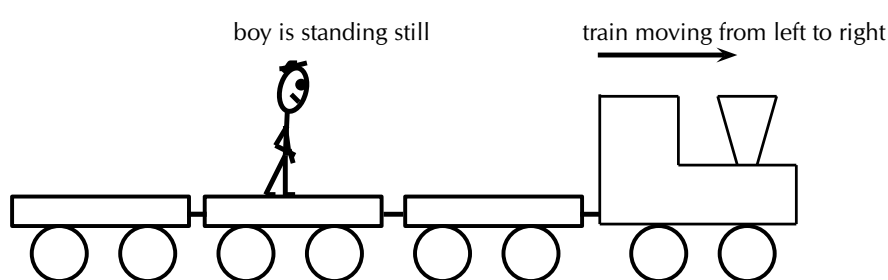



Figure 21.1: Frame of reference

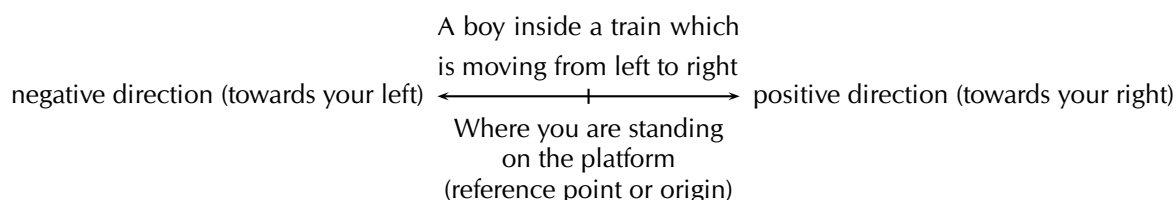
You can define different frames of reference for the same problem but the outcome, the physical results, will be the same. For example, a boy is standing still inside a train as it pulls out of a station. Both you and the boy define your location as the point of reference and the direction train is moving as a where you are standing as the point of reference and the direction the train is moving in as forward.

You are standing on the platform watching the train move from left to right. To you it looks as if the boy is moving from left to right, because relative to where you are standing (the platform), he is moving. According to the boy, and his *frame of reference* (the train), he is not moving.

A frame of reference must have an origin (where you are standing on the platform) and at least a positive direction. The train was moving from left to right, making to your right positive and to your left negative. If someone else was looking at the same boy, his frame of reference will be different. For example, if he was standing on the other side of the platform, the boy will be moving from right to left.

From your frame of reference the boy is moving from left to right.

A boy inside a train which is moving from left to right

negative direction (towards your left) ⟵ ⟶ positive direction (towards your right)

Where you are standing on the platform (reference point or origin)

For this chapter, we will only use frames of reference in the x-direction. By doing this we restrict ourselves to *one dimensional motion*. We can use the sign of the position value (positive or negative) to indicate the direction relative to the origin.

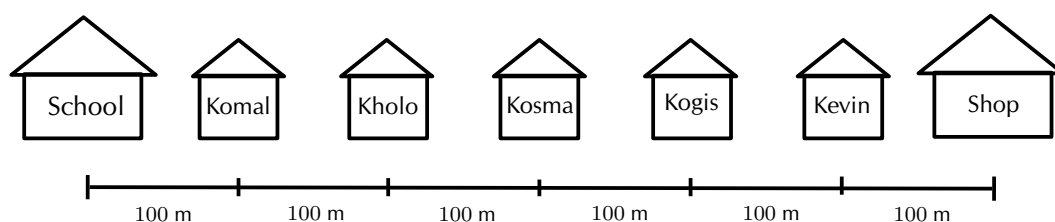
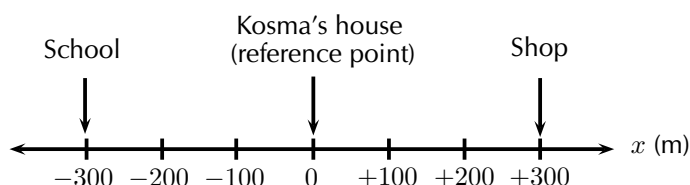
> ## *DEFINITION: One dimensional motion*
>
> An object is constrained to move back and forth along a line.

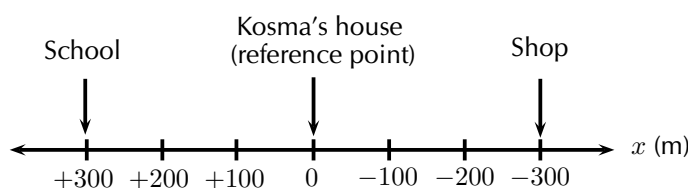
For example the blue dot in the figure below can only move along the x-axis.

Position *ESAGU*

> ### *DEFINITION: Position*
>
> Position is a measurement of a location, with reference to an origin.
>
> Quantity: Position (x) Unit name: metre Unit symbol: m

A position is a measurement of a location within a reference frame. This means that positions can be negative or positive depending on the choice for the reference frame's coordinate system. See video: VPgmf at www.everythingscience.co.za

Depending on which reference point we choose, we can say that the school is 300 m from Kosma's house (with Kosma's house as the reference point or origin) or 500 m from Kevin's house (with Kevin's house as the reference point or origin).

The shop is also 300 m from Kosma's house, but in the opposite direction as the school. When we choose a reference point, we have a positive direction and a negative direction. If we choose the direction **towards the school** as **negative**, then the direction towards the shop is positive. A negative direction is always opposite to the direction chosen as positive.

The origin is at Kosma's house and the position of the school is -300 m. Positions towards the left are defined as negative and positions towards the right are defined as positive.

Note that we could also choose the **positive** direction to be **towards the school**. In this case Kosma's house is still 300 m away from the school, but it is now in the positive direction.

The origin is at Kosma's house and the position of the school is $+300$ m. Positions towards the left are defined as positive and positions towards the right are defined as negative.

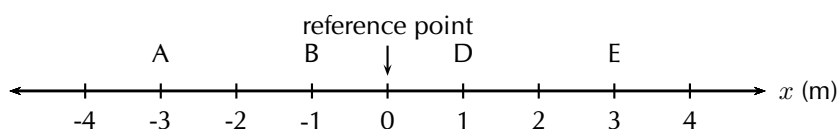
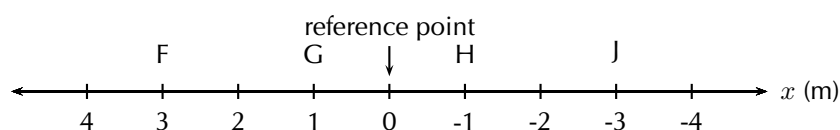
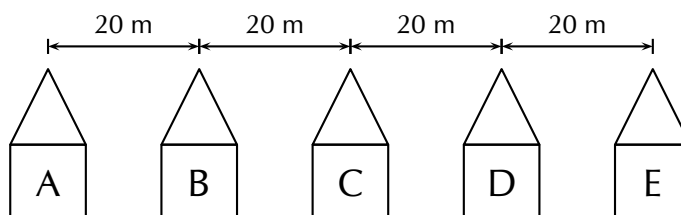
Group Discussion: Reference points

Divide into groups of 5 for this activity. On a straight line, choose a reference point. Since position can have both positive and negative values, discuss the advantages and disadvantages of choosing

1. either end of the line,
2. the middle of the line. (This reference point can also be called "the origin".)

Stand in a straight line, take turns choosing a different group member as the origin. Let the group member choose which direction along the line is positive. Everyone should then try to define their position. You don't need to measure your position very precisely but can just approximate it. It is important to understand whether your position is positive or negative for each difference origin and choice of coordinate system.
Notice that your position is different every time but that you didn't actually move. How you write an answer might be affected by the choice of a coordinate system but physical processes should never be affected.

Exercise 21 - 1

1. Write down the positions for objects at A, B, D and E. Do not forget the units.

2. Write down the positions for objects at F, G, H and J. Do not forget the units.

3. There are 5 houses on Newton Street, A, B, C, D and E. For all cases, assume that positions to the right are positive.

a. Draw a frame of reference with house A as the origin and write down the positions of houses B, C, D and E.

b. You live in house C. What is your position relative to house E?

c. What are the positions of houses A, B and D, if house B is taken as the reference point?

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(1.) 009g (2.) 009h (3.) 009i

Displacement and distance

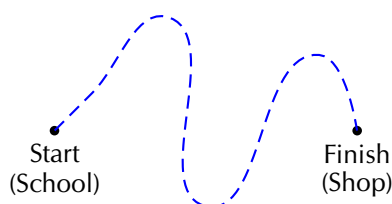
> ***Tip***
>
> The symbol Δ is read out as *delta*. Δ is a letter of the Greek alphabet and is used in Mathematics and Science to indicate a change in a certain quantity, or a final value minus an initial value. For example, Δx means change in x while Δt means change in t.

DEFINITION: Distance

Distance is the total length of the path taken in going from the initial position, $\vec{x}_i$, to the final position, $\vec{x}_f$. Distance is a scalar.

Quantity: Distance (D) Unit name: metre Unit symbol: m

In the simple map below you can see the path that winds because of a number of hills from a school to a nearby shop. The path is shown by a dashed line. The initial point, $\vec{x}_i$, is the school and the final point, $\vec{x}_f$, is the shop.

Distance is the length of dashed line. It is how far you have to walk along the path from the school to the shop.

DEFINITION: Displacement

Displacement is the change in an object's position. It is a vector that points from the initial position ($\vec{x}_i$) to the final position ($\vec{x}_f$).

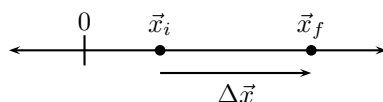
Quantity: Displacement ($\Delta\vec{x}$) Unit name: metre Unit symbol: m

The displacement of an object is defined as its change in position (final position minus initial position). Displacement has a magnitude and direction and is therefore a vector. For example, if the initial position of a car is $\vec{x}_i$ and it moves to a final position of $\vec{x}_f$, then the displacement is:

$$\boxed{\Delta\vec{x} = \vec{x}_f - \vec{x}_i}$$

To help visualise what the displacement vector looks like think back to the tail-to-head method. The displacement is the vector you add to the initial position vector to get a vector to the final position. However, subtracting an initial quantity from a final quantity happens often in Physics, so we use the shortcut Δ to mean *final - initial*. Therefore, displacement can be written:

$$\Delta\vec{x} = \vec{x}_f - \vec{x}_i$$

The following diagram illustrates the concept of displacement:

For example, if you roll a ball 5 m along a floor, in a straight line, then its displacement is 5 m, taking the direction of motion as positive, and the initial position as 0 m.

Displacement does not depend on the path travelled, but only on the initial and final positions. We use the word *distance* to describe how far an object travels along a particular path.

Tip

The words *initial* and *final* will be used very often in Physics. *Initial* refers to the situation in the beginning of the description/problem and *final* to the situation at the end. It will often happen that the final value is smaller than the initial value, such that the difference is negative. This is ok!

Tip

We will use D in this book, but you may see d used in other books.

Tip

We use the expression *'as the crow flies'* to mean a straight line between two points because birds can fly directly over many obstacles.

If we go back to the simple map repeated below you can see the path as before shown by a dashed line.

Distance is the length of dashed line. The displacement is different. Displacement is the straight-line distance from the starting point to the endpoint – from the school to the shop in the figure as shown by the solid arrow.

See video: VPgmo at www.everythingscience.co.za

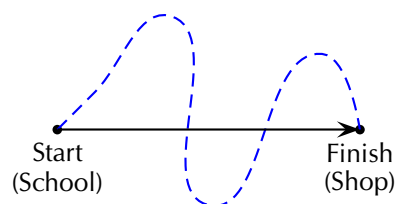
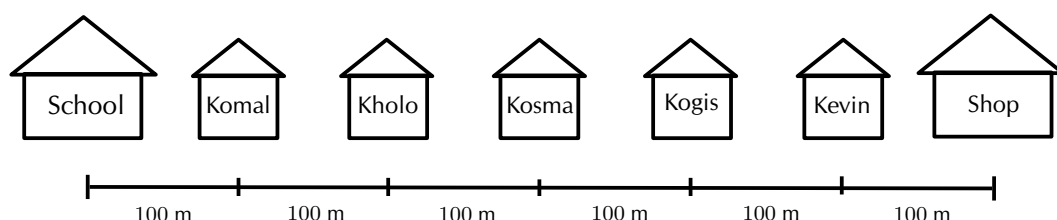



Illustration of distance and displacement

If we use the same situation as earlier we can explore the concepts in more detail. Consider our description of the location of the houses, school and the shop.

Komal walks to meet Kevin at his house before walking to school. What is Komal's displacement and what distance did he cover if he walks to school via Kevin's house?

Komal covers a distance of 400 m to Kevin's house and another 500 m from Kevin's house to the school. He covers a total distance of 900 m. His displacement, however, is only 100 m towards the school. This is because displacement only looks at the starting position (his house) and the end position (the school). It does not depend on the path he travelled.

To calculate his distance and displacement, we need to choose a reference point and a direction. Let's choose Komal's house as the reference point, and towards Kevin's house as the positive direction (which means that towards the school is negative). We would do the calculations as follows:

$$\begin{aligned}\text{Distance (D)} &= \text{path travelled} \\ &= 400\text{ m} + 500\text{ m} \\ &= 900\text{ m}\end{aligned}$$

$$\begin{aligned}\text{Displacement}(\Delta\vec{x}) &= \vec{x}_f - \vec{x}_i \\ &= -100\text{ m} + 0\text{ m} \\ &= -100\text{ m} \\ &= 100\text{ m (in the negative } x \text{ direction)}\end{aligned}$$

Very often in calculations you will get a negative answer. For example, Komal's displacement in the example above, is calculated as -100 m. The minus sign in front of the answer means that his displacement is 100 m in the opposite direction (opposite to the direction chosen as positive in the beginning of the question). When we start a calculation we choose a frame of reference and a positive direction. In the first example above, the reference point is Komal's house and the positive direction is towards Kevin's house. Therefore Komal's displacement is 100 m towards the school. Notice that distance has no direction,

but displacement has a direction.
Kevin walks to school with Komal and after school walks back home. What is Kevin's displacement and what distance did he cover? For this calculation we use Kevin's house as the reference point. Let's take towards the school as the positive direction.

$$\begin{aligned} \text{Distance (D)} &= \text{path travelled} \\ &= 500\ \text{m} + 500\ \text{m} \\ &= 1000\ \text{m} \end{aligned} \qquad \begin{aligned} \text{Displacement}(\Delta\vec{x}) &= \vec{x}_f - \vec{x}_i \\ &= 0\ \text{m} + 0\ \text{m} \\ &= 0\ \text{m} \end{aligned}$$

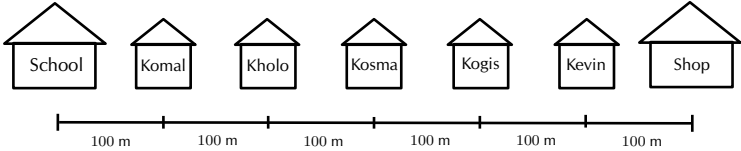
It is possible to have a displacement of 0 m and a distance that is not 0 m. This happens whenever you end at the same point you started.

Differences between distance and displacement

The differences between distance and displacement can be summarised as:

Distance	Displacement
1. depends on the path	1. independent of path taken
2. always positive	2. can be positive or negative
3. is a scalar	3. is a vector

Exercise 21 - 2

1. Use this figure to answer the following questions.

   a. Kogis walks to Kosma's house and then to school, what is her distance and displacement?
   b. Kholo walks to Kosma's house and then to school, what is her distance and displacement?
   c. Komal walks to the shop and then to school, what is his distance and displacement?
   d. What reference point did you use for each of the above questions?
2. You stand at the front door of your house (displacement, $\Delta\vec{x} = 0$ m). The street is 10 m away from the front door. You walk to the street and back again.

a. What is the distance you have walked?
b. What is your final displacement?
c. Is displacement a vector or a scalar? Give a reason for your answer.

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(1.) 009j (2.) 009k

Speed and velocity ESAGW

DEFINITION: Average speed

Average speed is the **distance** (D) travelled divided by the time (Δt) taken for the journey.
Quantity: average speed (v_{av}) Unit name: metre per second Unit symbol: $\text{m} \cdot \text{s}^{-1}$

DEFINITION: Average velocity

Average velocity is the **change in position** of a body divided by the time it took for the displacement to occur.
Quantity: average velocity ($\vec{v}_{av}$) Unit name: metre per second Unit symbol: $\text{m} \cdot \text{s}^{-1}$

Before moving on review the difference between distance and displacement. Sometimes the average speed can be a very big number while the average velocity is zero. See video:

at www.everythingscience.co.za

Average velocity is the rate of change of position. It tells us how much an object's position changes per unit of time. Velocity is a vector. We use the symbol $\vec{v}_{av}$ for average velocity.

If we have a displacement of $\Delta\vec{x}$ and a time taken of Δt, $\vec{v}_{av}$ is then defined as:

$$\begin{aligned}\text{average velocity (in m}\cdot\text{s}^{-1}) &= \frac{\text{change in position (in m)}}{\text{change in time (in s)}}\\ \vec{v}_{av} &= \frac{\Delta\vec{x}}{\Delta t}\end{aligned}$$

Velocity can be positive or negative. A positive velocity points in the direction you chose as positive in your coordinate system. A negative velocity points in the direction opposite to the positive direction.

Average speed (symbol v_{av}) is the distance travelled (D) divided by the time taken (Δt) for the journey. Distance and time are scalars and therefore speed will also be a scalar. Speed is calculated as follows:

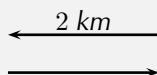
$$\text{average speed (in m}\cdot\text{s}^{-1}) = \frac{\text{distance (in m)}}{\text{time (in s)}}$$

$$v_{av} = \frac{D}{\Delta t}$$

Example 1: *Average speed and average velocity*

QUESTION

James walks 2 km away from home in 30 minutes. He then turns around and walks back home along the same path, also in 30 minutes. Calculate James' average speed and average velocity.

2 km

SOLUTION

Step 1 : ***Identify what information is given and what is asked for***
The question explicitly gives

- the distance and time out (2 km in 30 minutes)
- the distance and time back (2 km in 30 minutes)

Step 2 : ***Check that all units are SI units.***

The information is not in SI units and must therefore be converted.

To convert km to m, we know that:

$$\begin{aligned} 1 \text{ km} &= 1\ 000 \text{ m} \\ \therefore \quad 2 \text{ km} &= 2\ 000 \text{ m} \quad \text{(multiply both sides by 2.)} \end{aligned}$$

Similarly, to convert 30 minutes to seconds,

$$\begin{aligned} 1 \text{ min} &= 60\text{s} \\ \therefore \quad 30 \text{ min} &= 1\ 800 \text{ s} \quad \text{(multiply both sides by 30)} \end{aligned}$$

Step 3 : ***Determine James' displacement and distance.***

James started at home and returned home, so his displacement is 0 m.

$\Delta\vec{x} = 0$ m

James walked a total distance of 4000 m ($2\ 000$ m out and $2\ 000$ m back).

$D = 4\ 000$ m

Step 4 : ***Determine his total time.***

James took $1\ 800$ s to walk out and $1\ 800$ s to walk back.

$\Delta t = 3\ 600$ s

Step 5 : ***Determine his average speed***

$$\begin{aligned} v_{av} &= \frac{D}{\Delta t} \\ &= \frac{4\ 000 \text{ m}}{3\ 600 \text{ s}} \\ &= 1{,}11 \ \text{ m} \cdot \text{s}^{-1} \end{aligned}$$

Step 6 : ***Determine his average velocity***

$$\begin{aligned} \vec{v}_{av} &= \frac{\Delta\vec{x}}{\Delta t} \\ &= \frac{0 \text{ m}}{3\ 600 \text{ s}} \\ &= 0 \ \text{ m} \cdot \text{s}^{-1} \end{aligned}$$

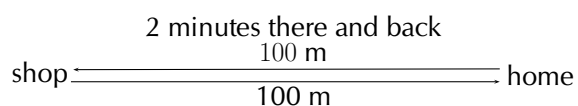
Differences between speed and velocity ESAGX

The differences between speed and velocity can be summarised as:

Speed	**Velocity**
1. depends on the path taken	1. independent of path taken
2. always positive	2. can be positive or negative
3. is a scalar	3. is a vector
4. no dependence on direction and so is only positive	4. direction can be determined from the sign convention used (i.e. positive or negative)

Additionally, an object that makes a round trip, i.e. travels away from its starting point and then returns to the same point has zero velocity but travels at a non-zero speed.

Exercise 21 - 3

1. Bongani has to walk to the shop to buy some milk. After walking 100 m, he realises that he does not have enough money, and goes back home. If it took him two minutes to leave and come back, calculate the following:
   - **a**. How long was he out of the house (the time interval Δt in seconds)?
   - **b**. How far did he walk (distance (D))?
   - **c**. What was his displacement ($\Delta\vec{x}$)?
   - **d**. What was his average velocity (in $\text{m}\cdot\text{s}^{-1}$)?
   - **e**. What was his average speed (in $\text{m}\cdot\text{s}^{-1}$)?

2. Bridget is watching a straight stretch of road from her classroom window. She can see two poles which she earlier measured to be 50 m apart. Using her stopwatch, Bridget notices that it takes 3 s for most cars to travel from the one pole to the other.

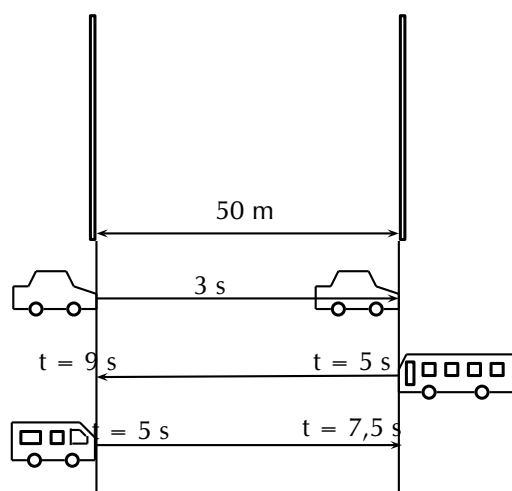
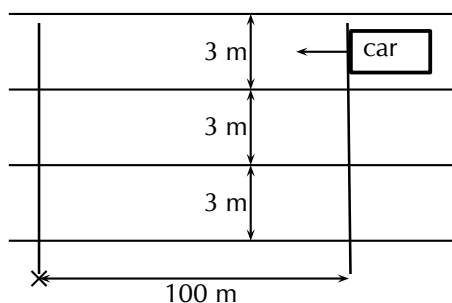
a. Using the equation for velocity ($\vec{v}_{av} = \frac{\Delta \vec{x}}{\Delta t}$), show all the working needed to calculate the velocity of a car travelling from the left to the right.

b. If Bridget measures the velocity of a red Golf to be $-16,67$ m · s^{-1}, in which direction was the Golf travelling? Bridget leaves her stopwatch running, and notices that at $t = 5,0$ s, a taxi passes the left pole at the same time as a bus passes the right pole. At time $t = 7,5$ s the taxi passes the right pole. At time $t = 9,0$ s, the bus passes the left pole.

c. How long did it take the taxi and the bus to travel the distance between the poles? (Calculate the time interval (Δt) for both the taxi and the bus).

d. What was the average velocity of the taxi and the bus?

e. What was the average speed of the taxi and the bus?

f. What was the average speed of taxi and the bus in km · h^{-1}?

3. A rabbit runs across a freeway. There is a car, 100 m away travelling towards the rabbit.

a. If the car is travelling at 120 km·h^{-1}, what is the car's speed in m·s^{-1}.

b. How long will it take the a car to travel 100 m?

c. If the rabbit is running at 10 km · h^{-1}, what is its speed in m · s^{-1}?

d. If the freeway has 3 lanes, and each lane is 3 m wide, how long will it take for the rabbit to cross all three lanes?

e. If the car is travelling in the furthermost lane from the rabbit, will the rabbit be able to cross all 3 lanes of the freeway safely?

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(1.) 009m (2.) 009n (3.) 009p

Investigation: *An exercise in safety*

Divide into groups of 4 and perform the following investigation. Each group will be performing the same investigation, but the aim for each group will be different.

1. Choose an aim for your investigation from the following list and formulate a hypothesis:
   - Do cars travel at the correct speed limit?
   - Is is safe to cross the road outside of a pedestrian crossing?
   - Does the colour of your car determine the speed you are travelling at?
   - Any other relevant question that you would like to investigate.
2. On a road that you often cross, measure out 50 m along a straight section, far away from traffic lights or intersections.
3. Use a stopwatch to record the time each of 20 cars take to travel the 50 m section you measured.
4. Design a table to represent your results. Use the results to answer the question posed in the aim of the investigation. You might need to do some more measurements for your investigation. Plan in your group what else needs to be done.
5. Complete any additional measurements and write up your investigation under the following headings:
   - Aim and Hypothesis
   - Apparatus
   - Method
   - Results
   - Discussion

- Conclusion

6. Answer the following questions:
   a. How many cars took less than 3 s to travel 50 m?
   b. What was the shortest time a car took to travel 50 m?
   c. What was the average time taken by the 20 cars?
   d. What was the average speed of the 20 cars?
   e. Convert the average speed to km · h^{-1}.

Acceleration

 ESAGY

DEFINITION: Average acceleration

Average acceleration is the change in average velocity divided by the time taken.
Quantity: Average acceleration ($\vec{a}_{av}$) Unit name: metre per second squared Unit symbol: m · s^{-2}

Acceleration is a measure of how fast the velocity of an object changes in time. If we have a change in velocity ($\Delta\vec{v}$) over a time interval (Δt), then the average acceleration ($\vec{a}_{av}$) is defined as:

$$\text{average acceleration (in m} \cdot \text{s}^{-2}) = \frac{\text{change in velocity (in m} \cdot \text{s}^{-1})}{\text{change in time (in s)}}$$

$$\vec{a}_{av} = \frac{\Delta\vec{v}}{\Delta t}$$

We only deal with problems with constant acceleration. This means that the average acceleration and the instantaneous acceleration are the same. To make things simpler we will

only talk about acceleration and not average or instantaneous. This is represented as $\vec{a}$. We can also have the magnitude of the acceleration. This is:

$$a = \frac{\Delta \vec{v}}{\Delta t}$$

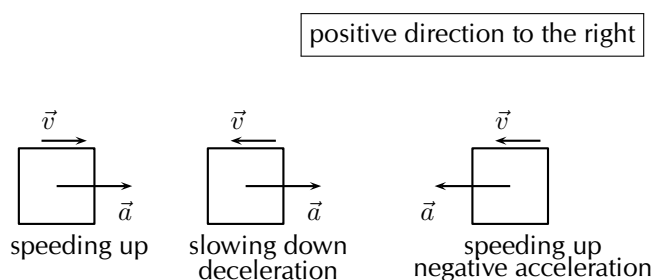
Acceleration is a vector. Acceleration does not provide any information about the motion, but only about how the motion changes. It is not possible to tell how fast an object is moving or in which direction from the acceleration alone.

See video: VPgly at www.everythingscience.co.za

Tip

Avoid the use of the word *deceleration* to refer to a negative acceleration. This word usually means *slowing down* and it is possible for an object to slow down with both a positive and negative acceleration, because the sign of the velocity of the object must also be taken into account to determine whether the body is slowing down or not.

Like velocity, acceleration can be negative or positive. We see that when the sign of the acceleration and the velocity are the same, the object is speeding up. If both velocity and acceleration are positive, the object is speeding up in a positive direction. If both velocity and acceleration are negative, the object is speeding up in a negative direction. We can see this in the following diagram:

positive direction to the right

If velocity is positive and acceleration is negative, then the object is slowing down. Similarly, if the velocity is negative and the acceleration is positive the object is slowing down. This is illustrated in the following worked example.

Example 2: Acceleration

QUESTION

A car accelerates uniformly from and initial velocity of 2 m·s^{-1} to a final velocity of 10 m·s^{1} in 8 seconds. It then slows down uniformly to a final velocity of 4 m·s^{-1} in 6 seconds. Calculate the acceleration of the car during the first 8 seconds and during the last 6 seconds.

SOLUTION

Step 1 : ***Choose a reference frame***

We choose the point where the car starts to accelerate as the origin and the direction in which the car is already moving as the positive direction.

Step 2 : ***Identify what information is given and what is asked for:***

Consider the motion of the car in two parts: the first 8 seconds and the last 6 seconds.

For the first 8 seconds:

$$\begin{aligned} \vec{v}_i &= 2 \text{ m} \cdot \text{s}^{-1} \\ \vec{v}_f &= 10 \text{ m} \cdot \text{s}^{-1} \\ t_i &= 0 \text{ s} \\ t_f &= 8 \text{ s} \end{aligned}$$

For the last 6 seconds:

$$\begin{aligned} \vec{v}_i &= 10 \text{ m} \cdot \text{s}^{-1} \\ \vec{v}_f &= 4 \text{ m} \cdot \text{s}^{-1} \\ t_i &= 8 \text{ s} \\ t_f &= 14 \text{ s} \end{aligned}$$

Step 3 : ***Calculate the acceleration.***

For the first 8 seconds:

$$\begin{aligned} a &= \frac{\Delta v}{\Delta t} \\ &= \frac{10}{8 \text{ s} - 0 \text{ s}} \\ &= 1 \text{ m} \cdot \text{s}^{-2} \end{aligned}$$

For the next 6 seconds:

$$\begin{aligned} a &= \frac{\Delta v}{\Delta t} \\ &= \frac{4}{14 \text{ s} - 8 \text{ s}} \\ &= -1 \text{ m} \cdot \text{s}^{-2} \end{aligned}$$

During the first 8 seconds the car had a positive acceleration. This means that its velocity increased. The velocity is positive so the car is speeding up. During the next 6 seconds the car had a negative acceleration. This means that its velocity decreased. The velocity is positive so the car is slowing down.

Exercise 21 - 4

1. An athlete is accelerating uniformly from an initial velocity of 0 m·s^{-1}to a final velocity of 4 m·s^{-1}in 2 seconds. Calculate his acceleration. Let the direction that the athlete is running in be the positive direction.
2. A bus accelerates uniformly from an initial velocity of 15 m·s^{-1}to a final velocity of 7 m·s^{-1}in 4 seconds. Calculate the acceleration of the bus. Let the direction of motion of the bus be the positive direction.
3. An aeroplane accelerates uniformly from an initial velocity of 100 m·s^{-1}to a velocity of 200 m·s^{-1}in 10 seconds. It then accelerates uniformly to a final velocity of 240 m·s^{-1}in 20 seconds. Let the direction of motion of the aeroplane be the positive direction.
   a. Calculate the acceleration of the aeroplane during the first 10 seconds

of the motion.

b. Calculate the acceleration of the aeroplane during the next 20 seconds of its motion.

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(1.) 009q (2.) 009r (3.) 009s

Instantaneous velocity and speed

ESAGZ

Sprinters taking off

Sprinters finishing race

Photographs by wwarby on Flickr.com

We have looked at the average velocity and speed but sometimes we want to be more precise about what is happening between the initial and final times in a problem.

Instantaneous velocity is the velocity at a specific instant in time. This can be different to the average velocity if the velocity isn't constant.

Look at the photographs of the sprinters in a race. Their velocity is different as they take off and as they end. Their average velocity for the race doesn't change but their instantaneous velocity, as captured in the "snapshots" of an instant in time does change. Their velocity in the photograph would be an instantaneous velocity.

Tip

An instant in time is different from the time taken or the time interval. It is therefore useful to use the symbol t for an instant in time (for example during the 4^{th} second) and the symbol Δt for the time taken (for example during the first 5 seconds of the motion).

DEFINITION: Instantaneous velocity

Instantaneous velocity is the change in position over the change in a very small time interval ($\Delta t \approx 0$).

Quantity: Instantaneous velocity ($\vec{v}$) Unit name: metre per second

Unit name: $\text{m} \cdot \text{s}^{-1}$

DEFINITION: Instantaneous speed

Instantaneous speed is the magnitude of instantaneous velocity.
Quantity: Instantaneous speed (v) Unit name: metre per second
Unit symbol: $\text{m} \cdot \text{s}^{-1}$

Instantaneous velocity is a vector. Instantaneous speed is the magnitude of instantaneous velocity. It has the same value but is not a vector so it has no direction.

Description of motion

ESAHA

The purpose of this chapter is to describe motion, and now that we understand the definitions of displacement, distance, velocity, speed and acceleration, we are ready to start using these ideas to describe how an object or person is moving. We will look at three ways of describing motion:

1. words
2. diagrams
3. graphs

These methods will be described in this section.

We will consider three types of motion: when the object is not moving (stationary object), when the object is moving at a constant velocity (uniform motion) and when the object is moving at a constant acceleration (motion at constant acceleration).

Stationary Object

ESAHB

The simplest motion that we can come across is that of a stationary object. A stationary object does not move and so its position does not change.

Consider an example, Vivian is waiting for a taxi. She is standing two metres from a stop street at $t = 0$ s. After one minute, at $t = 60$ s, she is still 2 metres from the stop street and after two minutes, at $t = 120$ s, also 2 metres from the stop street. Her position has not changed. Her displacement is zero (because his position is the same), her velocity is zero (because his displacement is zero) and her acceleration is also zero (because her velocity is not changing).

We can now draw graphs of position vs. time ($\vec{x}$ vs. t), velocity vs. time ($\vec{v}$ vs. t) and acceleration vs. time ($\vec{a}$ vs. t) for a stationary object. The graphs are shown below.

Vivian stands at a stop sign.

Photograph by Rob Boudon on Flickr.com

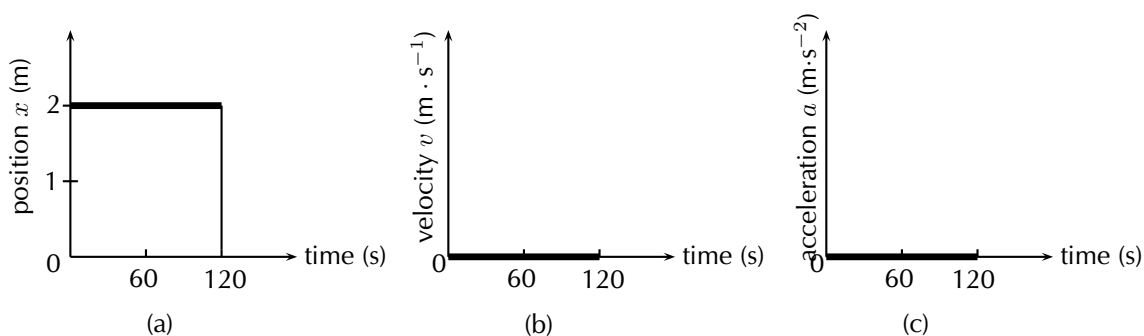



Figure 21.2: Graphs for a stationary object (a) position vs. time (b) velocity vs. time (c) acceleration vs. time.

Vivian's position is 2 metres in the positive direction from the stop street. If the stop street is taken as the reference point, her position remains at 2 metres for 120 seconds. The graph is a horizontal line at 2 m. The velocity and acceleration graphs are also shown. They are both horizontal lines on the x-axis. Since her position is not changing, her velocity is 0 m · s^{-1} and since velocity is not changing, acceleration is 0 m · s^{-2}.

DEFINITION: Gradient

(Recall from Mathematics) The gradient, m, of a line can be calculated by dividing the change in the y-value (dependent variable) by the change in the x-value (independent variable). $m = \frac{\Delta y}{\Delta x}$

Tip

The gradient of a position vs. time graph gives the average velocity, while the tangent of a position vs. time graph gives the instantaneous velocity.

Since we know that velocity is the rate of change of position, we can confirm the value for the velocity vs. time graph, by calculating the gradient of the $\vec{x}$ vs. t graph.

If we calculate the gradient of the $\vec{x}$ vs. t graph for a stationary object we get:

$$\begin{aligned} v &= \frac{\Delta \vec{x}}{\Delta t} \\ &= \frac{\vec{x}_f - \vec{x}_i}{t_f - t_i} \\ &= \frac{2 \text{ m} - 2 \text{ m}}{120 \text{ s} - 60 \text{ s}} \text{ (initial position = final position)} \\ &= 0 \text{ m} \cdot \text{s}^{-1} \text{ (for the time that Vivian is stationary)} \end{aligned}$$

Tip

The gradient of a velocity vs. time graph gives the average acceleration, while the tangent of a velocity vs. time graph gives the instantaneous acceleration.

Similarly, we can confirm the value of the acceleration by calculating the gradient of the velocity vs. time graph.

If we calculate the gradient of the $\vec{v}$ vs. t graph for a stationary object we get:

$$\begin{aligned} a &= \frac{\Delta v}{\Delta t} \\ &= \frac{\vec{v}_f - \vec{v}_i}{t_f - t_i} \\ &= \frac{0 \text{ m} \cdot \text{s}^{-1} - 0 \text{ m} \cdot \text{s}^{-1}}{120 \text{ s} - 60 \text{ s}} \\ &= 0 \text{ m} \cdot \text{s}^{-2} \end{aligned}$$

Tip

The area under the velocity vs. time graph gives the displacement.

Additionally, because the velocity vs. time graph is related to the position vs. time graph, we can use the area under the velocity vs. time graph to calculate the displacement of an object.

The displacement of the object is given by the area under the graph, which is 0 m. This is obvious, because the object is not moving.

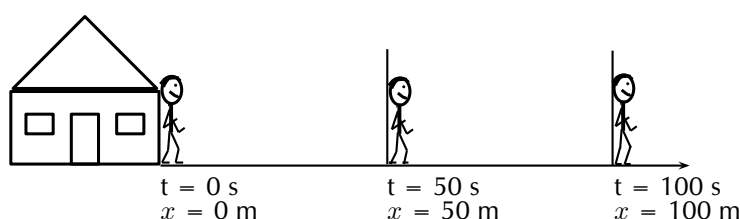
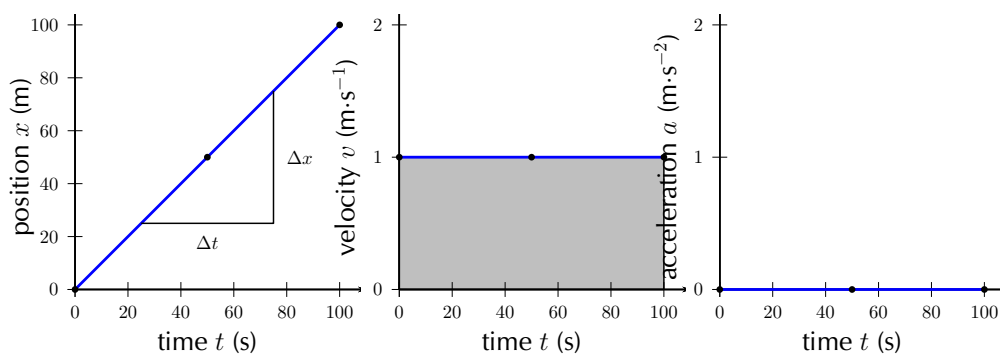
Motion at Constant Velocity

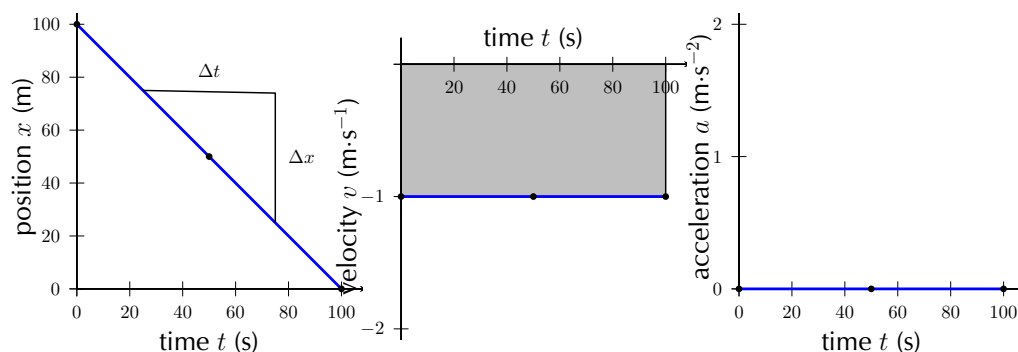
Motion at a constant velocity or *uniform motion* means that the position of the object is changing at the same rate.

Assume that Vivian takes 100 s to walk the 100 m to the taxi-stop every morning. If we assume that Vivian's house is the origin and the direction to the taxi is positive, then

Vivian's velocity is:

$$\begin{aligned} v &= \frac{\Delta \vec{x}}{\Delta t} \\ &= \frac{x_f - x_i}{t_f - t_i} \\ &= \frac{100 \text{ m} - 0 \text{ m}}{100 \text{ s} - 0 \text{ s}} \\ &= 1 \text{ m} \cdot \text{s}^{-1} \end{aligned}$$

Vivian's velocity is $1 \text{ m} \cdot \text{s}^{-1}$. This means that she walked 1 m in the first second, another metre in the second second, and another in the third second, and so on. For example, after 50 s she will be 50 m from home. Her position increases by 1 m every 1 s. A diagram of Vivian's position is shown below:

We can now draw graphs of position vs.time ($\vec{x}$ vs. t), velocity vs. time ($\vec{v}$ vs. t) and acceleration vs.time ($\vec{a}$ vs. t) for Vivian moving at a constant velocity. The graphs are shown here:

Graphs for motion at constant velocity (a) position vs. time (b) velocity vs. time (c) acceleration vs. time. The area of the shaded portion in the v vs. t graph corresponds to the object's displacement.

In the evening Vivian walks 100 m from the bus stop to her house in 100 s. Assume that Vivian's house is the origin. The following graphs can be drawn to describe the motion.

Graphs for motion with a constant negative velocity. The area of the shaded portion in the v vs.t graph corresponds to the object's displacement.

We see that the $\vec{v}$ vs. t graph is a horizontal line. If the velocity vs. time graph is a horizontal line, it means that the velocity is *constant* (not changing). Motion at a constant velocity is known as *uniform motion*. We can use the $\vec{x}$ vs. t to calculate the velocity by finding the gradient of the line.

$$\begin{aligned} v &= \frac{\Delta \vec{x}}{\Delta t} \\ &= \frac{\vec{x}_f - \vec{x}_i}{t_f - t_i} \\ &= \frac{0 \text{ m} - 100 \text{ m}}{100 \text{ s} - 0 \text{ s}} \\ &= -1 \text{ m} \cdot \text{s}^{-1} \end{aligned}$$

Vivian has a velocity of -1 m $\cdot$ s^{-1}, or 1 m $\cdot$ s^{-1} towards her house. You will notice that the $\vec{v}$ vs. t graph is a horizontal line corresponding to a velocity of -1 m $\cdot$ s^{-1}. The horizontal line means that the velocity stays the same (remains constant) during the motion. This is uniform velocity.

We can use the $\vec{v}$ vs. t to calculate the acceleration by finding the gradient of the line.

$$\begin{aligned} a &= \frac{\Delta \vec{v}}{\Delta t} \\ &= \frac{\vec{v}_f - \vec{v}_i}{t_f - t_i} \\ &= \frac{1 \text{ m} \cdot \text{s}^{-1} - 1 \text{ m} \cdot \text{s}^{-1}}{100 \text{ s} - 0 \text{ s}} \\ &= 0 \text{ m} \cdot \text{s}^{-2} \end{aligned}$$

Vivian has an acceleration of 0 m·s^{-2}. You will notice that the graph of $\vec{a}$ vs. t is a horizontal line corresponding to an acceleration value of 0 m $\cdot$ s^{-2}. There is no acceleration during the motion because his velocity does not change.

We can use the $\vec{v}$ vs. t graph to calculate the displacement by finding the area under the graph.

$$\begin{aligned}\Delta\vec{x} &= \text{Area under graph}\\ &= \ell \times\ b\\ &= 100\ (-1)\\ &= -100\ \text{m}\end{aligned}$$

This means that Vivian has a displacement of 100 m towards her house.

Exercise 21 - 5

1. Use the graphs in Figure 21.6 to calculate each of the following:
   a. Calculate Vivian's velocity between 50 s and 100 s using the x vs. t graph. Hint: Find the gradient of the line.
   b. Calculate Vivian's acceleration during the whole motion using the v vs. t graph.
   c. Calculate Vivian's displacement during the whole motion using the v vs. t graph.
2. Thandi takes 200 s to walk 100 m to the bus stop every morning. In the evening Thandi takes 200 s to walk 100 m from the bus stop to her home.
   a. Draw a graph of Thandi's position as a function of time for the morning (assuming that Thandi's home is the reference point). Use the gradient of the x vs. t graph to draw the graph of velocity vs. time. Use the gradient of the v vs. t graph to draw the graph of acceleration vs. time.
   b. Draw a graph of Thandi's position as a function of time for the evening (assuming that Thandi's home is the origin). Use the gradient of the x vs. t graph to draw the graph of velocity vs. time. Use the gradient of the v vs. t graph to draw the graph of acceleration vs. time.
   c. Discuss the differences between the two sets of graphs in questions 2 and 3.

(1.) 009t (2.) 009u

General experiment: *Motion at constant velocity*

Aim:
To measure the position and time during motion at constant velocity and determine the average velocity as the gradient of a "Position vs. Time" graph.

Apparatus:
A battery operated toy car, stopwatch, meter stick or measuring tape.

Method:

1. Work with a friend. Copy the table below into your workbook.
2. Complete the table by timing the car as it travels each distance.
3. Time the car twice for each distance and take the average value as your accepted time.
4. Use the distance and average time values to plot a graph of "Distance vs. Time" *onto graph paper*. Stick the graph paper into your workbook. (Remember that "A vs. B" always means "y vs. x").
5. Insert all axis labels and units onto your graph.
6. Draw the best straight line through your data points.
7. Find the gradient of the straight line. This is the average velocity.

Results:

Distance (m)	Time (s)		
	1	2	Ave.
0			
0,5			
1,0			
1,5			
2,0			
2,5			
3,0			

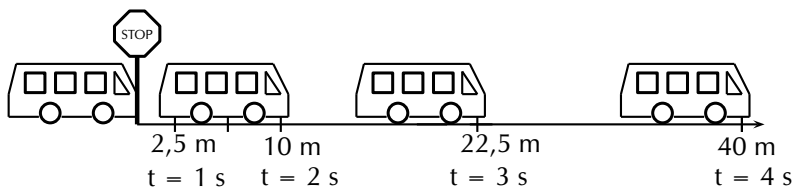
Conclusions:
Answer the following questions in your workbook:

1. Did the car travel with a constant velocity?

2. How can you tell by looking at the "Distance vs. Time" graph if the velocity is constant?
3. How would the "Distance vs. Time" graph look for a car with a faster velocity?
4. How would the "Distance vs. Time" graph look for a car with a slower velocity?

Motion at constant acceleration

The final situation we will be studying is motion at *constant acceleration*. We know that acceleration is the rate of change of velocity. So, if we have a constant acceleration, this means that the velocity changes at a constant rate.

Let's look at our first example of Vivian waiting at the taxi stop again. A taxi arrived and Vivian got in. The taxi stopped at the stop street and then accelerated in the positive direction as follows: After 1 s the taxi covered a distance of $2,5$ m, after 2 s it covered 10 m, after 3 s it covered $22,5$ m and after 4 s it covered 40 m. The taxi is covering a larger distance every second. This means that it is accelerating.

To calculate the velocity of the taxi you need to calculate the gradient of the line at each second:

$$\begin{aligned}\vec{v}_{1s} &= \frac{\Delta\vec{x}}{\Delta t}\\ &= \frac{\vec{x}_f - \vec{x}_i}{t_f - t_i}\\ &= \frac{5\text{ m} - 0\text{ m}}{1,5\text{ s} - 0,5\text{ s}}\\ &= 5\text{ m}\cdot\text{s}^{-1}\end{aligned}$$

$$\begin{aligned}\vec{v}_{2s} &= \frac{\Delta\vec{x}}{\Delta t} \\ &= \frac{\vec{x}_f - \vec{x}_i}{t_f - t_i} \\ &= \frac{15\text{ m} - 5\text{ m}}{2,5\text{ s} - 1,5\text{ s}} \\ &= 10\text{ m}\cdot\text{s}^{-1}\end{aligned}$$

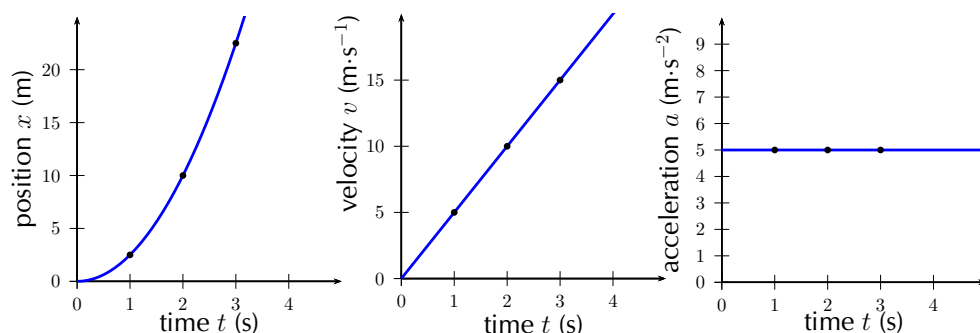
$$\begin{aligned}\vec{v}_{3s} &= \frac{\Delta\vec{x}}{\Delta t} \\ &= \frac{\vec{x}_f - \vec{x}_i}{t_f - t_i} \\ &= \frac{30\text{ m} - 15\text{ m}}{3,5\text{ s} - 2,5\text{ s}} \\ &= 15\text{ m}\cdot\text{s}^{-1}\end{aligned}$$

From these velocities, we can draw the velocity-time graph which forms a straight line.

The acceleration is the gradient of the v vs. t graph and can be calculated as follows:

$$\begin{aligned}a &= \frac{\Delta\vec{v}}{\Delta t} \\ &= \frac{\vec{v}_f - \vec{v}_i}{t_f - t_i} \\ &= \frac{15\text{ m}\cdot\text{s}^{-1} - 5\text{ m}\cdot\text{s}^{-1}}{3\text{ s} - 1\text{ s}} \\ &= 5\text{ m}\cdot\text{s}^{-2}\end{aligned}$$

The acceleration does not change during the motion (the gradient stays constant). This is motion at constant or uniform acceleration.

The graphs for this situation are shown below:

Graphs for motion with a constant acceleration starting from rest.

Velocity from acceleration vs. time graphs

Just as we used velocity vs. time graphs to find displacement, we can use acceleration vs. time graphs to find the velocity of an object at a given moment in time. We simply calculate the area under the acceleration vs. time graph, at a given time. In the graph below, showing an object at a constant positive acceleration, the increase in velocity of the object after 2 seconds corresponds to the shaded portion.

$$\begin{aligned} v &= \text{area of rectangle} = a \times \Delta t \\ &= 5\ \text{m} \cdot \text{s}^{-2} \times 2\ \text{s} \\ &= 10\ \text{m} \cdot \text{s}^{-1} \end{aligned}$$

The velocity of the object at $t = 2$ s is therefore 10 m · s^{-1}.

Summary of Graphs ESAHE

The relation between graphs of position, velocity and acceleration as functions of time is summarised in the next figure.

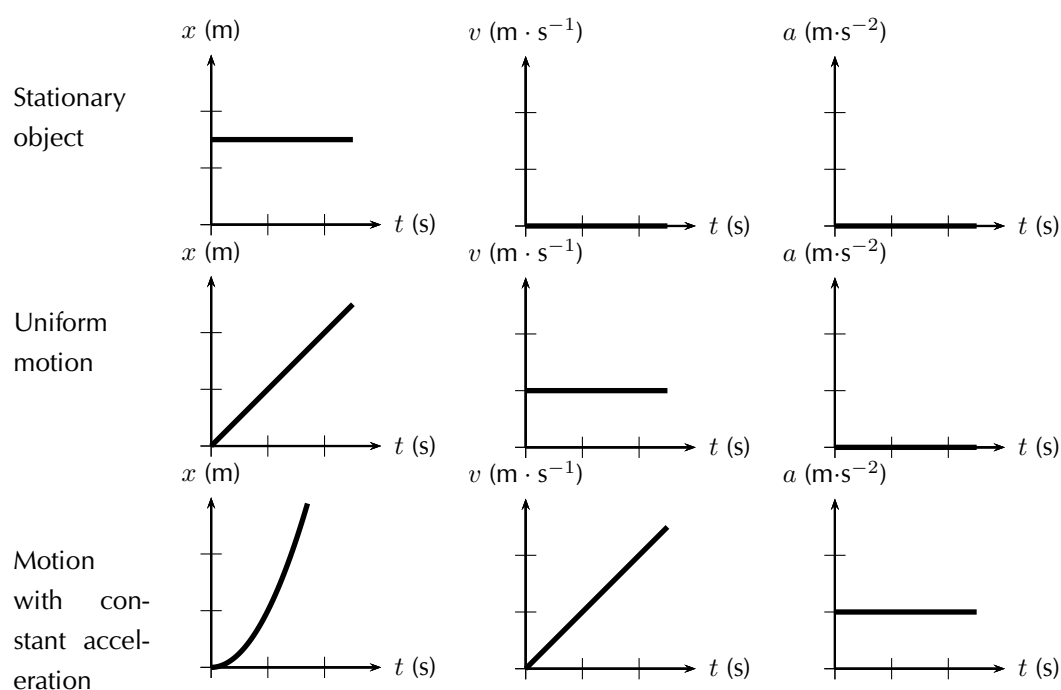



Figure 21.3: Position-time, velocity-time and acceleration-time graphs.

Tip

The description of the motion represented by a graph should include the following (where possible):

1. whether the object is moving in the positive or negative direction
2. whether the object is at rest, moving at constant velocity or moving at constant positive acceleration (speeding up) or constant negative acceleration (slowing down)

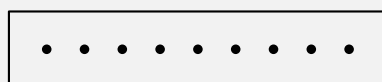
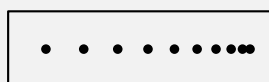
You will also often be required to draw graphs based on a description of the motion in words or from a diagram. Remember that these are just different methods of presenting the same information. If you keep in mind the general shapes of the graphs for the different types of motion, there should not be any difficulty with explaining what is happening.

Formal experiment: *Position versus time using a ticker timer*

Aim:

To measure the position and time during motion and to use that data to plot a "Position vs. Time" graph.

Apparatus:

Trolley, ticker tape apparatus, tape, graph paper, ruler, ramp

Method:

1. Work with a friend. Copy the table below into your workbook.
2. Attach a length of tape to the trolley.
3. Run the other end of the tape through the ticker timer.
4. Start the ticker timer going and roll the trolley down the ramp.
5. Repeat steps 1 - 3.
6. On each piece of tape, measure the distance between successive dots. Note these distances in the table below.
7. Use the frequency of the ticker timer to work out the time intervals between successive dots. Note these times in the table below,
8. Work out the average values for distance and time.
9. Use the average distance and average time values to plot a graph of "Distance vs. Time" *onto graph paper*. Stick the graph paper into your workbook. (Remember that "A vs. B" always means "y vs. x").
10. Insert all axis labels and units onto your graph.
11. Draw the best straight line through your data points.

Results:

Distance (m)			Time (s)		
1	2	Ave.	1	2	Ave.

Discussion:

Describe the motion of the trolley down the ramp.

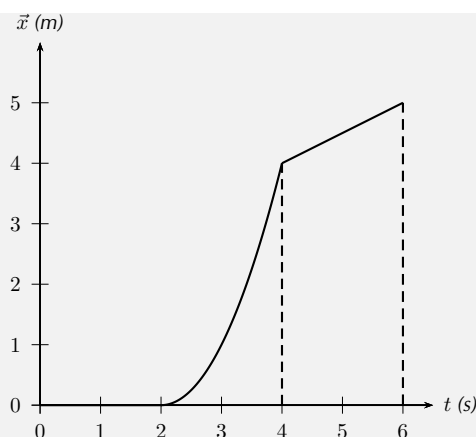
Worked examples

ESAHF

The worked examples in this section demonstrate the types of questions that can be asked about graphs.

Example 3: *Description of motion based on a position-time graph*

QUESTION

The position vs. time graph for the motion of a car is given below. Draw the corresponding velocity vs. time and acceleration vs. time graphs, and then describe the motion of the car.

SOLUTION

Step 1 : ***Identify what information is given and what is asked for***

The question gives a position vs. time graph and the following three things are required:

1. Draw a v vs. t graph.
2. Draw an a vs. t graph.
3. Describe the motion of the car.

To answer these questions, break the motion up into three sections: 0 – 2 seconds, 2 – 4 seconds and 4 – 6 seconds.

Step 2 : ***Velocity vs. time graph for 0 – 2 seconds***

For the first 2 seconds we can see that the position (and hence the displacement) remains constant - so the object is not moving, thus it has zero velocity during this time. We can reach this conclusion by another path too: remember that the gradient of a displacement vs. time graph is the velocity. For the first 2 seconds we can see that the displacement vs. time graph is a horizontal line, i.e.. it has a gradient of zero. Thus the velocity during this time is zero and the object is stationary.

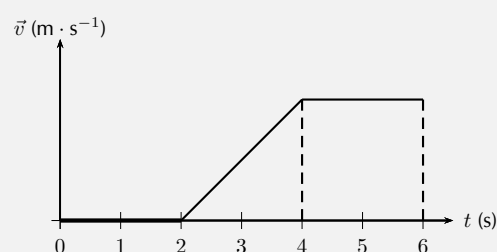
Step 3 : ***Velocity vs. time graph for 2 – 4 seconds***

For the next 2 seconds, displacement is increasing with time so the object is moving. Looking at the gradient of the displacement graph we can see that it is not constant. In fact, the slope is getting steeper (the gradient is increasing) as time goes on. Thus, remembering that the gradient of a displacement vs. time graph is the velocity, the velocity must be increasing with time during this phase.

Step 4 : ***Velocity vs. time graph for 4 – 6 seconds***

For the final 2 seconds we see that displacement is still increasing with time, but this time the gradient is constant, so we know that the object

is now travelling at a constant velocity, thus the velocity vs. time graph will be a horizontal line during this stage. We can now draw the graphs:

So our velocity vs. time graph looks like this one below. Because we haven't been given any values on the vertical axis of the displacement vs. time graph, we cannot figure out what the exact gradients are and therefore what the values of the velocities are. In this type of question it is just important to show whether velocities are positive or negative, increasing, decreasing or constant.

Once we have the velocity vs. time graph its much easier to get the acceleration vs. time graph as we know that the gradient of a velocity vs. time graph is the just the acceleration.

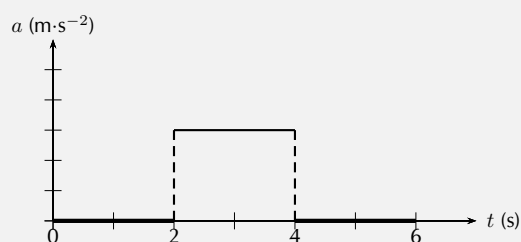
Step 5 : ***Acceleration vs. time graph for 0 – 2 seconds***

For the first 2 seconds the velocity vs. time graph is horizontal and has a value of zero, thus it has a gradient of zero and there is no acceleration during this time. (This makes sense because we know from the displacement time graph that the object is stationary during this time, so it can't be accelerating).

Step 6 : ***Acceleration vs. time graph for 2 – 4 seconds***

For the next 2 seconds the velocity vs. time graph has a positive gradient. This gradient is not changing (i.e. its constant) throughout these 2 seconds so there must be a constant positive acceleration.

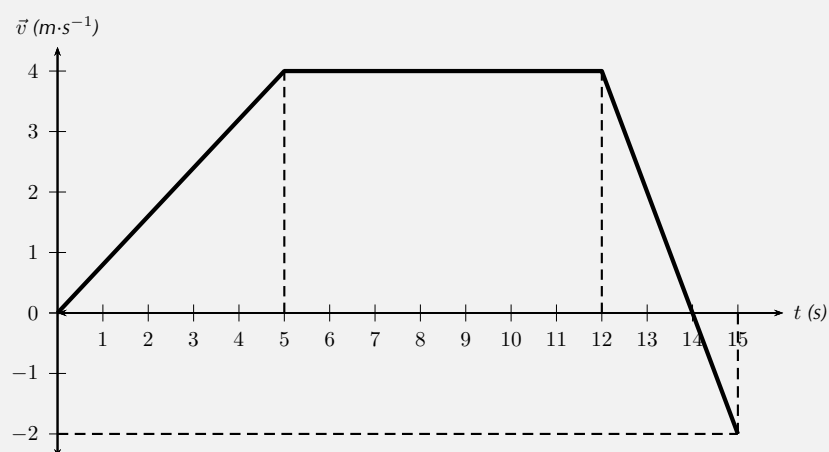
Step 7 : ***Acceleration vs. time graph for 4 – 6 seconds***

For the final 2 seconds the object is travelling with a constant velocity. During this time the gradient of the velocity vs. time graph is once again zero, and thus the object is not accelerating. The acceleration vs. time graph looks like this:

Step 8 : ***A description of the object's motion***

A brief description of the motion of the object could read something like this: At $t = 0$ s and object is stationary at some position and remains stationary until $t = 2$ s when it begins accelerating. It accelerates in a positive direction for 2 seconds until $t = 4$ s and then travels at a constant velocity for a further 2 seconds.

Example 4: *Calculations from a velocity vs. time graph*

QUESTION

The velocity vs. time graph of a truck is plotted below. Calculate the distance and displacement of the truck after 15 seconds.

SOLUTION

Step 1 : ***Decide how to tackle the problem***

We are asked to calculate the distance and displacement of the car. All we need to remember here is that we can use the area between the velocity vs. time graph and the time axis to determine the distance and displacement.

Step 2 : ***Determine the area under the velocity vs. time graph***

Break the motion up: 0 – 5 seconds, 5 – 12 seconds, 12 – 14 seconds and 14 – 15 seconds.

For 0 – 5 seconds: The displacement is equal to the area of the triangle on the left:

$$\begin{aligned} \text{Area}_\triangle &= \frac{1}{2}\, b \times h \\ &= \frac{1}{2} \times 5\ \text{s}\ \times 4\ \text{m}\cdot\text{s}^{-1} \\ &= 10\ \text{m} \end{aligned}$$

For 5 – 12 seconds: The displacement is equal to the area of the rectangle:

$$\begin{aligned} \text{Area}_\square &= \ell \times b \\ &= 7\ \text{s}\ \times 4\ \text{m}\cdot\text{s}^{-1} \\ &= 28\ \text{m}^2 \end{aligned}$$

For 12 – 14 seconds the displacement is equal to the area of the triangle above the time axis on the right:

$$\begin{aligned} \text{Area}_\triangle &= \frac{1}{2}\, b \times h \\ &= \frac{1}{2} \times 2\ \text{s}\ \times 4\ \text{m}\cdot\text{s}^{-1} \\ &= 4\ \text{m} \end{aligned}$$

For 14 – 15 seconds the displacement is equal to the area of the triangle below the time axis:

$$\begin{aligned} \text{Area}_\triangle &= \frac{1}{2}\, b \times h \\ &= \frac{1}{2} \times 1\ \text{s}\ \times 2\ \text{m}\cdot\text{s}^{-1} \\ &= 1\ \text{m} \end{aligned}$$

Step 3 : ***Determine the total distance of the car***

Now the total distance of the car is the sum of all of these areas:

$$\begin{aligned} D &= 10\ \text{m} + 28\ \text{m} + 4\ \text{m} + 1\ \text{m} \\ &= 43\ \text{m} \end{aligned}$$

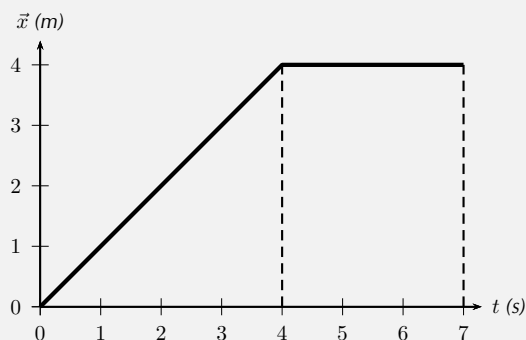
Step 4 : ***Determine the total displacement of the car***

Now the total displacement of the car is just the sum of all of these areas. HOWEVER, because in the last second (from $t = 14$ s to $t = 15$ s) the velocity of the car is negative, it means that the car was going in the opposite direction, i.e. back where it came from! So, to find the total displacement, we have to add the first 3 areas (those with positive displacements) and subtract the last one (because it is a displacement in the opposite direction).

$$\begin{aligned} \Delta\vec{x} &= 10\ \text{m} + 28\ \text{m} + 4\ \text{m} - 1\ \text{m} \\ &= 41\ \text{m in the positive direction} \end{aligned}$$

Example 5: *Velocity from a position vs. time graph*

QUESTION

The position vs. time graph below describes the motion of an athlete.

1. *What is the velocity of the athlete during the first 4 seconds?*
2. *What is the velocity of the athlete from $t = 4$ s to $t = 7$ s?*

SOLUTION

Step 1 : ***The velocity during the first 4 seconds***

The velocity is given by the gradient of a position vs. time graph. During the first 4 seconds, this is

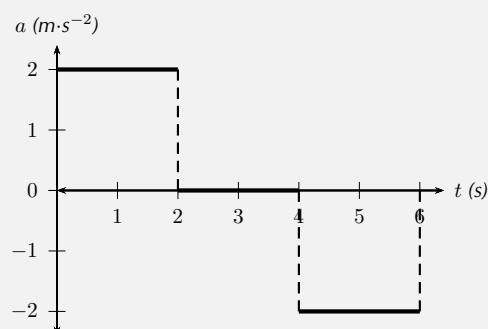
$$\begin{aligned}\vec{v} &= \frac{\Delta\vec{x}}{\Delta t} \\ &= \frac{4\text{ m} - 0\text{ m}}{4\text{ s} - 0\text{ s}} \\ &= 1\ \text{m}\cdot\text{s}^{-1}\end{aligned}$$

Step 2 : ***The velocity during the last 3 seconds***

For the last 3 seconds we can see that the displacement stays constant. The graph shows a horizontal line and therefore the gradient is zero. Thus $v = 0\ \text{m}\cdot\text{s}^{-1}$.

Example 6: Drawing a v vs. t graph from an a vs. t graph

QUESTION

The acceleration vs. time graph for a car starting from rest, is given below. Calculate the velocity of the car and hence draw the velocity vs. time graph.

SOLUTION

Step 1 : ***Calculate the velocity values by using the area under each part of the graph.***

The motion of the car can be divided into three time sections: 0 – 2 seconds; 2 – 4 seconds and 4 – 6 seconds. To be able to draw the velocity vs. time graph, the velocity for each time section needs to be calculated. The velocity is equal to the area of the square under the graph:

For 0 – 2 seconds:

$$\begin{aligned} \text{Area}_\square &= \ell \times b \\ &= 2\ \text{s} \times 2\ \text{m} \cdot \text{s}^{-2} \\ &= 4\ \text{m} \cdot \text{s}^{-1} \end{aligned}$$

The velocity of the car is 4 m·s^{-1} at t = 2s.

For 2 – 4 seconds:

$$\begin{aligned} \text{Area}_\square &= \ell \times b \\ &= 2\ \text{s} \times 0\ \text{m} \cdot \text{s}^{-2} \\ &= 0\ \text{m} \cdot \text{s}^{-1} \end{aligned}$$

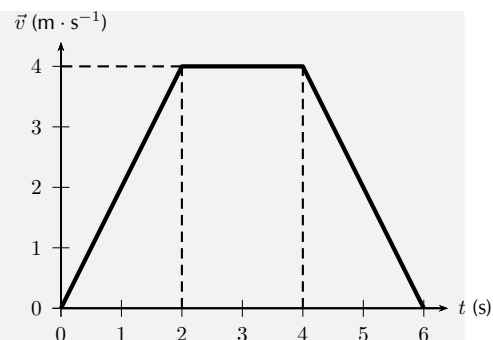
The velocity of the car is 0 m · s^{-1} from $t = 2$ s to $t = 4$ s.

For 4 – 6 seconds:

$$\begin{aligned} \text{Area}_\square &= \ell \times b \\ &= 2\ \text{s} \times -2\ \text{m} \cdot \text{s}^{-2} \\ &= -4\ \text{m} \cdot \text{s}^{-1} \end{aligned}$$

The acceleration had a negative value, which means that the velocity is decreasing. It starts at a velocity of 4 m · s^{-1} and decreases to 0 m · s^{-1}.

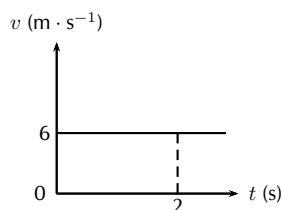
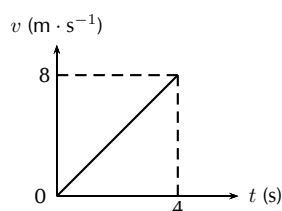
Step 2 : ***Now use the values to draw the velocity vs. time graph.***

The velocity vs. time graph looks like this:

Exercise 21 - 6

1. A car is parked 10 m from home for 10 minutes. Draw a displacement-time, velocity-time and acceleration-time graphs for the motion. Label all the axes.

2. A bus travels at a constant velocity of 12 m · s^{-1}for 6 seconds. Draw the displacement-time, velocity-time and acceleration-time graph for the motion. Label all the axes.

3. An athlete runs with a constant acceleration of 1 m · s^{-2} for 4 s. Draw the acceleration-time, velocity-time and displacement time graphs for the motion. Accurate values are only needed for the acceleration-time and velocity-time graphs.

4. The following velocity-time graph describes the motion of a car. Draw the displacement-time graph and the acceleration-time graph and explain the motion of the car according to the three graphs.

5. The following velocity-time graph describes the motion of a truck. Draw the displacement-time graph and the acceleration-time graph and explain the motion of the truck according to the three graphs.

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(1.) 009v (2.) 009w (3.) 009x (4.) 009y (5.) 009z

See simulation: (Simulation: VPrwb at www.everythingscience.co.za)

Equations of motion

ESAHG

In this section we will look at the third way to describe motion. We have looked at describing motion in terms of words and graphs. In this section we examine equations that can be used to describe motion.

This section is about solving problems relating to uniformly accelerated motion. In other words, motion at constant acceleration.

The following are the variables that will be used in this section:

$$\begin{aligned}
\vec{v}_i &= \text{initial velocity } (\text{m}\cdot\text{s}^{-1}) \text{ at } t = 0 \text{ s} \\
\vec{v}_f &= \text{final velocity } (\text{m}\cdot\text{s}^{-1}) \text{ at time } t \\
\Delta\vec{x} &= \text{displacement (m)} \\
t &= \text{time (s)} \\
\Delta t &= \text{time interval (s)} \\
\vec{a} &= \text{acceleration } (\text{m}\cdot\text{s}^{-2})
\end{aligned}$$

An alternate convention for some of the variables exists that you will likely encounter so

FACT

Galileo Galilei of Pisa, Italy, was the first to determined the correct mathematical law for acceleration: the total distance covered, starting from rest, is proportional to the square of the time. He also concluded that objects retain their velocity unless a force – often friction – acts upon them, refuting the accepted Aristotelian hypothesis that objects "naturally" slow down and stop unless a force acts upon them. This principle was incorporated into Newton's laws of motion (1st law).

here is a list for reference purposes:

$$\vec{u} = \text{initial velocity } (\text{m} \cdot \text{s}^{-1}) \text{ at } t = 0 \text{ s}$$
$$\vec{v} = \text{final velocity } (\text{m} \cdot \text{s}^{-1}) \text{ at time } t$$
$$\vec{s} = \text{displacement (m)}$$

In this book we will use the first convention.

$$\vec{v}_f = \vec{v}_i + \vec{a}t \quad (21.1)$$
$$\Delta\vec{x} = \frac{(\vec{v}_i + \vec{v}_f)}{2}t \quad (21.2)$$
$$\Delta\vec{x} = \vec{v}_i t + \frac{1}{2}\vec{a}t^2 \quad (21.3)$$
$$v_f^2 = v_i^2 + 2\vec{a}\Delta\vec{x} \quad (21.4)$$

The questions can vary a lot, but the following method for answering them will always work. Use this when attempting a question that involves motion with constant acceleration. You need any three known quantities ($\vec{v}_i$, $\vec{v}_f$, $\Delta\vec{x}$, t or $\vec{a}$) to be able to calculate the fourth one.

Problem solving strategy:

1. Read the question carefully to identify the quantities that are given. Write them down.
2. Identify the equation to use. *Write it down!!!*
3. Ensure that all the values are in the correct units and fill them in your equation.
4. Calculate the answer and check your units.

Example 7: *Equations of motion*

QUESTION

A racing car is travelling North. It accelerates uniformly covering a distance of 725 m in 10 s. If it has an initial velocity of 10 m · s^{-1}, find its acceleration.

SOLUTION

Step 1 : ***Identify what information is given and what is asked for***

We are given:

$$\begin{aligned}\vec{v}_i &= 10\ \text{m}\cdot\text{s}^{-1}\\ \Delta\vec{x} &= 725\ \text{m}\\ t &= 10\ \text{s}\\ \vec{a} &= ?\end{aligned}$$

Step 2 : ***Find an equation of motion relating the given information to the acceleration***

If you struggle to find the correct equation, find the quantity that is not given and then look for an equation that has this quantity in it.

We can use Equation 21.3

$$\Delta\vec{x} = \vec{v}_i t + \frac{1}{2}\vec{a}t^2$$

Step 3 : ***Substitute your values in and find the answer***

$$\begin{aligned}\Delta\vec{x} &= \vec{v}_i t + \frac{1}{2}\vec{a}t^2\\ 725\ \text{m} &= (10\ \text{m}\cdot\text{s}^{-1}\times 10\ \text{s}) + \frac{1}{2}\vec{a}\times(10\ \text{s})^2\\ 725\ \text{m} - 100\ \text{m} &= (50\ \text{s}^2)\ \vec{a}\\ \vec{a} &= 12,5\ \text{m}\cdot\text{s}^{-2}\end{aligned}$$

Step 4 : ***Quote the final answer***

The racing car is accelerating at 12,5 m·s^{-2} North.

Example 8: Equations of motion I

QUESTION

A motorcycle, travelling East, starts from rest, moves in a straight line with a constant acceleration and covers a distance of 64 m in 4 s. Calculate

- *its acceleration*
- *its final velocity*
- *at what time the motorcycle had covered half the total distance*
- *what distance the motorcycle had covered in half the total time.*

SOLUTION

Step 1 : ***Identify what information is given and what is asked for***

We are given:

$$\begin{aligned}
\vec{v}_i &= 0 \text{ m} \cdot \text{s}^{-1} \text{(because the object starts from rest.)} \\
\Delta\vec{x} &= 64 \text{ m} \\
t &= 4 \text{ s} \\
\vec{a} &= ? \\
\vec{v}_f &= ? \\
t &= ? \text{ at half the distance } \Delta\vec{x} = 32 \text{ m.} \\
\Delta\vec{x} &= ? \text{ at half the time } t = 2 \text{ s.}
\end{aligned}$$

All quantities are in SI units.

Step 2 : ***Acceleration: Find a suitable equation to calculate the acceleration***

We can use Equations 21.3

$$\Delta\vec{x} = \vec{v}_i t + \frac{1}{2}\vec{a}t^2$$

Step 3 : ***Substitute the values and calculate the acceleration***

$$\begin{aligned}
\Delta\vec{x} &= \vec{v}_i t + \frac{1}{2}\vec{a}t^2 \\
64 \text{ m} &= (0 \text{ m} \cdot \text{s}^{-1} \times 4 \text{ s}) + \frac{1}{2}\vec{a} \times (4 \text{ s})^2 \\
64 \text{ m} &= (8 \text{ s}^2)\vec{a} \\
\vec{a} &= 8 \text{ m} \cdot \text{s}^{-2} \text{ East}
\end{aligned}$$

Step 4 : ***Final velocity: Find a suitable equation to calculate the final velocity***

We can use Equation 21.1 - remember we now also know the acceleration of the object.

$$\vec{v}_f = \vec{v}_i + \vec{a}t$$

Step 5 : ***Substitute the values and calculate the final velocity***

$$\begin{aligned} \vec{v}_f &= \vec{v}_i + at \\ \vec{v}_f &= 0 \text{ m}\cdot\text{s}^{-1} + (8 \text{ m}\cdot\text{s}^{-2})(4 \text{ s}) \\ &= 32 \text{ m}\cdot\text{s}^{-1} \text{ East} \end{aligned}$$

Step 6 : ***Time at half the distance: Find an equation to calculate the time***

We can use Equation 21.3:

$$\begin{aligned} \Delta\vec{x} &= \vec{v}_i + \frac{1}{2}\vec{a}t^2 \\ 32 \text{ m} &= (0 \text{ m}\cdot\text{s}^{-1})t + \frac{1}{2}(8 \text{ m}\cdot\text{s}^{-2})(t)^2 \\ 32 \text{ m} &= 0 + (4 \text{ m}\cdot\text{s}^{-2})t^2 \\ 8 \text{ s}^2 &= t^2 \\ t &= 2,83 \text{ s} \end{aligned}$$

Step 7 : ***Distance at half the time: Find an equation to relate the distance and time***

Half the time is 2 s, thus we have $\vec{v}_i$, $\vec{a}$ and t - all in the correct units. We can use Equation 21.3 to get the distance:

$$\begin{aligned} \Delta\vec{x} &= \vec{v}_i t + \frac{1}{2}at^2 \\ &= (0 \text{ m}\cdot\text{s}^{-1})(2 \text{ s}) + \frac{1}{2}(8 \text{ m}\cdot\text{s}^{-2})(2 \text{ s})^2 \\ &= 16 \text{ m East} \end{aligned}$$

Exercise 21 - 7

1. A car starts off at 10 m·s^{-1} and accelerates at 1 m·s^{-2} for 10 s. What is its final velocity?

2. A train starts from rest, and accelerates at 1 m·s^{-2} for 10 s. How far does it move?

3. A bus is going 30 m·s^{-1} and stops in 5 s. What is its stopping distance for this speed?

4. A racing car going at 20 m·s^{-1} stops in a distance of 20 m. What is its acceleration?

5. A ball has a uniform acceleration of 4 m·s^{-1}. Assume the ball starts from rest. Determine the velocity and displacement at the end of 10 s.

6. A motorcycle has a uniform acceleration of 4 m·s^{-1}. Assume the motorcycle has an initial velocity of 20 m·s^{-1}. Determine the velocity and displacement at the end of 12 s.

7. An aeroplane accelerates uniformly such that it goes from rest to 144 km·hr^{-1}in 8 s. Calculate the acceleration required and the total distance that it has travelled in this time.

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(1.) 00a0 (2.) 00a1 (3.) 00a2 (4.) 00a3 (5.) 00a4 (6.) 00a5 (7.) 00a6

Extension: Finding the equations of motion *ESAHH*

The following does not form part of the syllabus and can be considered additional information.

Derivation of 21.1

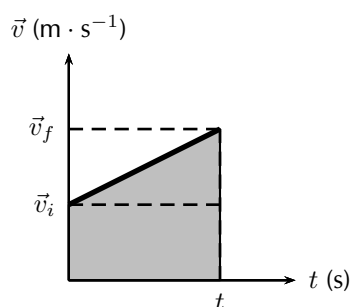
According to the definition of acceleration:

$$\vec{a} = \frac{\Delta\vec{v}}{t}$$

where $\Delta\vec{v}$ is the change in velocity, i.e. $\Delta v = \vec{v}_f$ - $\vec{v}_i$. Thus we have

$$\begin{aligned}\vec{a} &= \tfrac{\vec{v}_f - \vec{v}_i}{t} \\ \vec{v}_f &= \vec{v}_i + \vec{a}t\end{aligned}$$

Derivation of 21.2

We have seen that displacement can be calculated from the area under a velocity vs. time graph. For *uniformly accelerated motion* the most complicated velocity vs. time graph we can have is a straight line. Look at the graph below - it represents an object with a starting velocity of $\vec{v}_i$, accelerating to a final velocity $\vec{v}_f$ over a total time t.

To calculate the final displacement we must calculate the area under the graph - this is just the area of the rectangle added to the area of the triangle. This portion of the graph has been shaded for clarity.

$$\begin{aligned}\text{Area}_\triangle &= \tfrac{1}{2}b \times h \\ &= \tfrac{1}{2}t \times (v_f - v_i) \\ &= \tfrac{1}{2}v_f t - \tfrac{1}{2}v_i t\end{aligned}$$

$$\begin{aligned}\text{Area}_\square &= \ell \times b \\ &= t \times v_i \\ &= v_i t\end{aligned}$$

$$\begin{aligned} \text{Displacement} &= \text{Area}_{\Box} + \text{Area}_{\triangle} \\ \Delta\vec{x} &= v_i t + \frac{1}{2} v_f t - \frac{1}{2} v_i t \\ \Delta\vec{x} &= \frac{(v_i + v_f)}{2} t \end{aligned}$$

Derivation of 21.3

This equation is simply derived by eliminating the final velocity v_f in 21.2. Remembering from 21.1 that

$$\vec{v}_f = \vec{v}_i + \vec{a}t$$

then 21.2 becomes

$$\begin{aligned} \Delta\vec{x} &= \frac{\vec{v}_i + \vec{v}_i + \vec{a}t}{2} t \\ &= \frac{2\vec{v}_i t + \vec{a}t^2}{2} \\ \Delta\vec{x} &= \vec{v}_i t + \frac{1}{2}\vec{a}t^2 \end{aligned}$$

Derivation of 21.4

This equation is just derived by eliminating the time variable in the above equation. From 21.1 we know

$$t = \frac{\vec{v}_f - \vec{v}_i}{a}$$

Substituting this into 21.3 gives

$$
\begin{aligned}
\Delta\vec{x} &= \vec{v}_i\left(\frac{\vec{v}_f-\vec{v}_i}{a}\right)+\frac{1}{2}a\left(\frac{\vec{v}_f-\vec{v}_i}{\vec{a}}\right)^2 \\
&= \frac{\vec{v}_i\vec{v}_f}{\vec{a}}-\frac{\vec{v}_i^2}{\vec{a}}+\frac{1}{2}\vec{a}\left(\frac{\vec{v}_f^2-2\vec{v}_i\vec{v}_f+\vec{v}_i^2}{\vec{a}^2}\right) \\
&= \frac{\vec{v}_i\vec{v}_f}{\vec{a}}-\frac{\vec{\vec{v}}_i^2}{\vec{a}}+\frac{\vec{v}_f^2}{2\vec{a}}-\frac{\vec{v}_i\vec{v}_f}{\vec{a}}+\frac{\vec{v}_i^2}{2\vec{a}} \\
2\vec{a}\Delta\vec{x} &= -2\vec{v}_i^2+\vec{v}_f^2+\vec{v}_i^2 \\
\vec{v}_f^2 &= \vec{v}_i^2+2\vec{a}\Delta\vec{x}
\end{aligned}
$$

This gives us the final velocity in terms of the initial velocity, acceleration and displacement and is independent of the time variable.

Applications in the real-world ESAHI

What we have learnt in this chapter can be directly applied to road safety. We can analyse the relationship between speed and stopping distance. The following worked example illustrates this application.

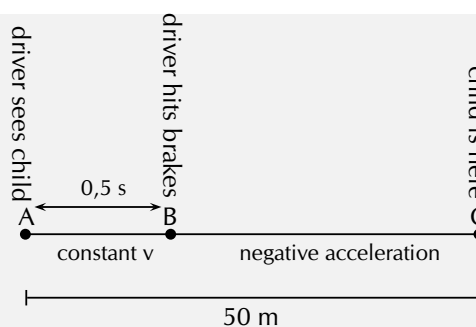
Example 9: *Stopping distance*

QUESTION

A truck is travelling at a constant velocity of 10 m · $s^{-1}$when the driver sees a child 50 m in front of him in the road. He hits the brakes to stop the truck. The truck accelerates at a rate of -1.25 m·s^{-2}. His reaction time to hit the brakes is 0,5 seconds. Will the truck hit the child?

SOLUTION

Step 1 : ***Analyse the problem and identify what information is given***

It is useful to draw a time-line like this one:

We need to know the following:

- What distance the driver covers before hitting the brakes.
- How long it takes the truck to stop after hitting the brakes.
- What total distance the truck covers to stop.

Step 2 : ***Calculate the distance AB***

Before the driver hits the brakes, the truck is travelling at constant velocity. There is no acceleration and therefore the equations of motion are not used. To find the distance travelled, we use:

$$\begin{aligned} v &= \frac{d}{t} \\ 10 &= \frac{d}{0,5} \\ d &= 5 \text{ m} \end{aligned}$$

The truck covers 5 m before the driver hits the brakes.

Step 3 : ***Calculate the time BC***

We have the following for the motion between B and C:

$$\begin{aligned} \vec{v}_i &= 10 \text{ m} \cdot \text{s}^{-1} \\ \vec{v}_f &= 0 \text{ m} \cdot \text{s}^{-1} \\ a &= -1,25 \text{ m} \cdot \text{s}^{-2} \\ t &= ? \end{aligned}$$

We can use Equation 21.1

$$\begin{aligned} \vec{v}_f &= \vec{v}_i + at \\ 0 &= 10 \text{ m} \cdot \text{s}^{-1} + (-1,25 \text{ m} \cdot \text{s}^{-2})t \\ -10 \text{ m} \cdot \text{s}^{-1} &= (-1,25 \text{ m} \cdot \text{s}^{-2})t \\ t &= 8 \text{ s} \end{aligned}$$

Step 4 : ***Calculate the distance BC***

For the distance we can use Equation 21.2 or Equation 21.3. We will

use Equation 21.2:

$$\Delta\vec{x} = \frac{(\vec{v}_i + \vec{v}_f)}{2}t$$
$$\Delta\vec{x} = \frac{10+0}{s}(8)$$
$$\Delta\vec{x} = 40 \text{ m}$$

Step 5 : ***Write the final answer***

The total distance that the truck covers is $d_{AB} + d_{BC} = 5 + 40 = 45$ meters. The child is 50 meters ahead. The truck will not hit the child.

Chapter 21 | Summary

See the summary presentation (Presentation: VPgjl at www.everythingscience.co.za)

- A reference point is a point from where you take your measurements.
- A frame of reference is a reference point with a set of directions.
- Your position is where you are located with respect to your reference point.
- The displacement of an object is how far it is from the reference point. It is the shortest distance between the object and the reference point. It has magnitude and direction because it is a vector.
- The distance of an object is the length of the path travelled from the starting point to the end point. It has magnitude only because it is a scalar.
- Speed (v) is the distance covered (D) divided by the time taken (Δt):

$$v = \frac{D}{\Delta t}$$

- Average velocity ($\vec{v}_{av}$) is the displacement ($\Delta\vec{x}$) divided by the time taken (Δt):

$$\vec{v}_{av} = \frac{\Delta\vec{x}}{\Delta t}$$

- Instantaneous speed is the speed at a specific instant in time.
- Instantaneous velocity is the velocity at a specific instant in time.

- Acceleration ($\vec{a}$) is the change in velocity ($\Delta\vec{v}$) over a time interval (Δt):

$$\vec{a} = \frac{\Delta\vec{v}}{\Delta t}$$

- The gradient of a position - time graph (x vs. t) gives the velocity.
- The gradient of a velocity - time graph (v vs. t) gives the acceleration.
- The area under a velocity - time graph (v vs. t) gives the displacement.
- The area under an acceleration - time graph (a vs. t) gives the velocity.
- The graphs of motion are summarised in Figure 21.3.
- The equations of motion are used where constant acceleration takes place:

$$\begin{aligned} v_f &= v_i + at \\ \Delta\vec{x} &= \tfrac{(v_i+v_f)}{2}t \\ \Delta\vec{x} &= v_i t + \tfrac{1}{2}at^2 \\ \vec{v}_f^2 &= \vec{v}_i^2 + 2a\Delta\vec{x} \end{aligned}$$

Physical Quantities			
Quantity	**Vector**	**Unit name**	**Unit symbol**
Position (x)	-	metre	m
Distance (D)	-	metre	m
Displacement ($\Delta\vec{x}$)	✓	metre	m
Speed (v_{av})	-	metre per second	m · s^{-1}
Average velocity ($\vec{v}_{av}$)	✓	metre per second	m · s^{-1}
Instantaneous velocity ($\vec{v}$)	✓	metre per second	m · s^{-1}
Instantaneous speed (v)	-	metre per second	m · s^{-1}
Instantaneous acceleration ($\vec{a}$)	✓	metre per second per second	m · s^{-2}
Average acceleration ($\vec{a}_{av}$)	✓	metre per second per second	m · s^{-2}
Magnitude of acceleration (a)	-	metre per second per second	m · s^{-2}

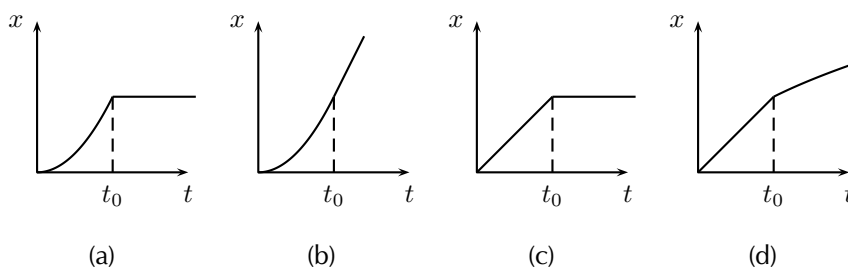
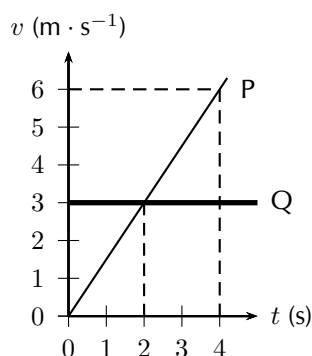
Table 21.1: Units used in **motion in one dimension**

Chapter 21 End of chapter exercises

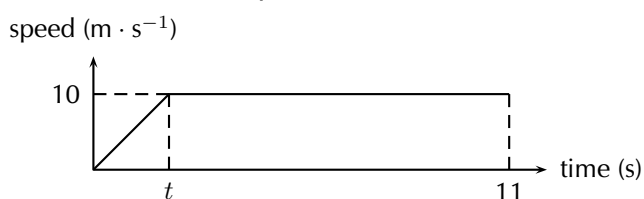
1. Give one word/term for the following descriptions.
   a. The shortest path from start to finish.
   b. A physical quantity with magnitude and direction.
   c. The quantity defined as a change in velocity over a time period.
   d. The point from where you take measurements.
   e. The distance covered in a time interval.
   f. The velocity at a specific instant in time.
2. Choose an item from column B that match the description in column A. Write down only the letter next to the question number. You may use an item from column B more than once.

Column A	Column B
a. The area under a velocity - time graph	gradient
b. The gradient of a velocity - time graph	area
c. The area under an acceleration - time graph	velocity
d. The gradient of a position - time graph	displacement
	acceleration
	slope

3. Indicate whether the following statements are TRUE or FALSE. Write only "true" or "false". If the statement is false, write down the correct statement.

   a. A scalar is the displacement of an object over a time interval.
   b. The position of an object is where it is located.
   c. The sign of the velocity of an object tells us in which direction it is travelling.
   d. The acceleration of an object is the change of its displacement over a period in time.
4. [SC 2003/11] A body accelerates uniformly from rest for t_0 seconds after which it continues with a constant velocity. Which graph is the correct representation of the body's motion?

5. [SC 2003/11] The velocity-time graphs of two cars are represented by P and Q as shown

The difference in the distance travelled by the two cars (in m) after 4 s is ...

(a) 12
(b) 6
(c) 2
(d) 0

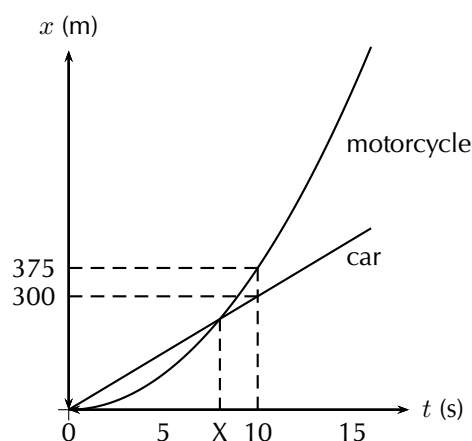
6. [IEB 2005/11 HG] The graph that follows shows how the speed of an athlete varies with time as he sprints for 100 m.

Which of the following equations can be used to correctly determine the time t for which he accelerates?

(a) $100 = (10)(11) - \frac{1}{2}(10)t$
(b) $100 = (10)(11) + \frac{1}{2}(10)t$
(c) $100 = 10t + \frac{1}{2}(10)t^2$
(d) $100 = \frac{1}{2}(0)t + \frac{1}{2}(10)t^2$

7. [SC 2002/03 HG1] In which one of the following cases will the distance covered and the magnitude of the displacement be the same?

(a) A girl climbs a spiral staircase.
(b) An athlete completes one lap in a race.
(c) A raindrop falls in still air.

(d) A passenger in a train travels from Cape Town to Johannesburg.

8. [SC 2003/11] A car, travelling at constant velocity, passes a stationary motor cycle at a traffic light. As the car overtakes the motorcycle, the motorcycle accelerates uniformly from rest for 10 s. The following displacement-time graph represents the motions of both vehicles from the traffic light onwards.

(a) Use the graph to find the magnitude of the constant velocity of the car.

(b) Use the information from the graph to show by means of calculation that the magnitude of the acceleration of the motorcycle, for the first 10 s of its motion is 7,5 m·s^{-2}.

(c) Calculate how long (in seconds) it will take the motorcycle to catch up with the car (point X on the time axis).

(d) How far behind the motorcycle will the car be after 15 seconds?

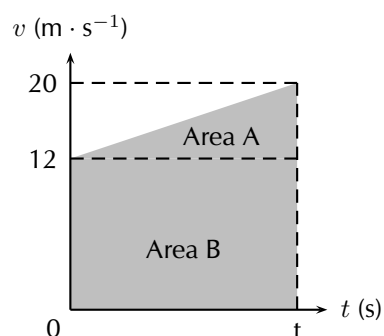
9. [IEB 2005/11 HG] Which of the following statements is *true* of a body that accelerates uniformly?

(a) Its rate of change of position with time remains constant.

(b) Its position changes by the same amount in equal time intervals.

(c) Its velocity increases by increasing amounts in equal time intervals.

(d) Its rate of change of velocity with time remains constant.

10. [IEB 2003/11 HG1] The velocity-time graph for a car moving along a straight horizontal road is shown below.

Which of the following expressions gives the magnitude of the average velocity of the car?

(a) $\frac{\text{Area A}}{t}$

(b) $\frac{\text{Area A} + \text{Area B}}{t}$

(c) $\frac{\text{Area B}}{t}$

(d) $\frac{\text{Area A} - \text{Area B}}{t}$

11. [SC 2002/11 SG] A car is driven at 25 $m \cdot s^{-1}$ in a municipal area. When the driver sees a traffic officer at a speed trap, he realises he is travelling too fast. He immediately applies the brakes of the car while still 100 m away from the speed trap.

(a) Calculate the magnitude of the minimum acceleration which the car must have to avoid exceeding the speed limit, if the municipal speed limit is 16.6 $m \cdot s^{-1}$.

(b) Calculate the time from the instant the driver applied the brakes until he reaches the speed trap. Assume that the car's velocity, when reaching the trap, is 16.6 $m \cdot s^{-1}$.

12. A traffic officer is watching his speed trap equipment at the bottom of a valley. He can see cars as they enter the valley 1 km to his left until they leave the valley 1 km to his right. Nelson is recording the times of cars entering and leaving the valley for a school project. Nelson notices a white Toyota enter the valley at 11:01:30 and leave the valley at 11:02:42. Afterwards, Nelson hears that the traffic officer recorded the Toyota doing 140 $km{\cdot}hr^{-1}$.

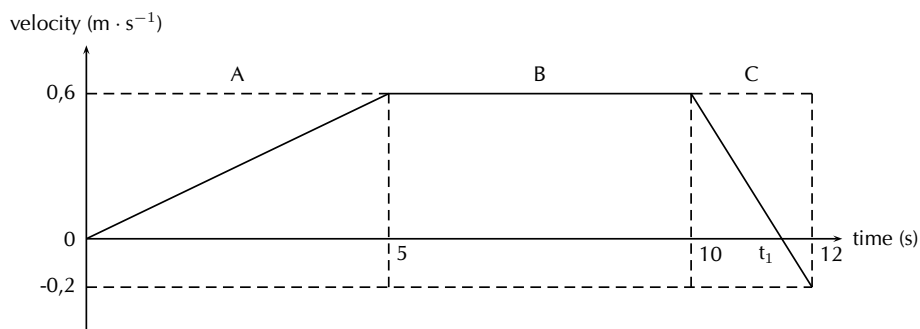
(a) What was the time interval (Δt) for the Toyota to travel through the valley?

(b) What was the average speed of the Toyota?

(c) Convert this speed to $km{\cdot}hr^{-1}$.

(d) Discuss whether the Toyota could have been travelling at 140$km{\cdot}hr^{-1}$ at the bottom of the valley.

(e) Discuss the differences between the instantaneous speed (as measured by the speed trap) and average speed (as measured by Nelson).

13. [IEB 2003/11HG] A velocity-time graph for a ball rolling along a track is shown below. The graph has been divided up into 3 sections, A, B and C for easy reference. (Disregard any effects of friction.)

(a) Use the graph to determine the following:

i. the speed 5 s after the start

ii. the distance travelled in Section A

iii. the acceleration in Section C

(b) At time t_1 the velocity-time graph intersects the time axis. Use an appropriate equation of motion to calculate the value of time t_1 (in s).

(c) Sketch a displacement-time graph for the motion of the ball for these 12 s. (You do not need to calculate the actual values of the displacement for each time interval, but do pay attention to the general shape of this graph during each time interval.)

14. In towns and cities, the speed limit is 60 $km \cdot hr^{-1}$. The length of the average car is 3.5 m, and the width of the average car is 2 m. In order to cross the road, you need to be able to walk further than the width of a car, before that car reaches you. To cross safely, you should be able to walk at least 2 m further than the width of the car (4 m in total), before the car reaches you.

(a) If your walking speed is 4 $km \cdot hr^{-1}$, what is your walking speed in $m \cdot s^{-1}$?

(b) How long does it take you to walk a distance equal to the width of the average car?

(c) What is the speed in $m \cdot s^{-1}$ of a car travelling at the speed limit in a town?

(d) How many metres does a car travelling at the speed limit travel, in the same time that it takes you to walk a distance equal to the width of car?

(e) Why is the answer to the previous question important?

(f) If you see a car driving toward you, and it is 28 m away (the same as the length of 8 cars), is it safe to walk across the road?

(g) How far away must a car be, before you think it might be safe to cross? How many car-lengths is this distance?

15. A bus on a straight road starts from rest at a bus stop and accelerates at 2 $m \cdot s^{-2}$ until it reaches a speed of 20 $m \cdot s^{-1}$. Then the bus travels for 20 s at a constant speed until the driver sees the next bus stop in the distance. The driver applies the brakes, stopping the bus in a uniform manner in 5 s.

(a) How long does the bus take to travel from the first bus stop to the second bus stop?

(b) What is the average velocity of the bus during the trip?

More practice video solutions or help at www.everythingscience.co.za

(1.) 00a7 (2.) 00a8 (3.) 00a9 (4.) 00aa (5.) 00ab (6.) 00ac
(7.) 00ad (8.) 00ae (9.) 00af (10.) 00ag (11.) 00ah (12.) 00ai
(13.) 00aj (14.) 00ak (15.) 00am

Mechanical energy 22

Introduction

All objects have energy. The word energy comes from the Greek word energeia ($\acute{\epsilon}\nu\acute{\epsilon}\rho\gamma\epsilon\iota\alpha$), meaning activity or operation. Energy is closely linked to mass and cannot be created or destroyed. In this chapter we will consider gravitational potential and kinetic energy. See introductory video: (Video: VPgjm at www.everythingscience.co.za)

Potential energy

The potential energy of an object is generally defined as the energy an object has because of its position relative to other objects that it interacts with. There are different kinds of potential energy such as gravitational potential energy, chemical potential energy, electrical potential energy, to name a few. In this section we will be looking at gravitational potential energy. See video: VPfhw at www.everythingscience.co.za

DEFINITION: Potential energy

Potential energy is the energy an object has due to its position or state.

DEFINITION: Gravitational potential energy

Gravitational potential energy is the energy an object has due to its position in a gravitational field relative to some reference point.
Quantity: Gravitational potential energy (E_P) Unit name: Joule Unit symbol: J

In the case of Earth, *gravitational* potential energy is the energy of an object due to its position above the surface of the Earth. The symbol E_P is used to refer to gravitational potential energy. You will often find that the words potential energy are used where *gravitational* potential energy is meant. We can define gravitational potential energy as:

$$\boxed{E_P = mgh}$$

where E_P = potential energy (measured in joules, J)

m = mass of the object (measured in kg)

g = gravitational acceleration ($9,8$ m · s^{-2})

h = *perpendicular* height from the reference point (measured in m)

Tip

You may sometimes see potential energy written as PE. We will not use this notation in this book, but you may see it in other books.

You can treat the gravitational acceleration, g, as a constant and you will learn more about it in grade 11 and 12.

Let's look at the case of a suitcase, with a mass of 1 kg, which is placed at the top of a 2 m high cupboard. By lifting the suitcase against the force of gravity, we give the suitcase potential energy. We can calculate its gravitational potential energy using the equation defined above as:

$$\begin{aligned} E_P &= mgh \\ &= (1\text{kg})(9,8\text{m} \cdot \text{s}^{-2})(2\text{m}) = 19,6 \text{ J} \end{aligned}$$

If the suitcase falls off the cupboard, it will lose its potential energy. Halfway down to the floor, the suitcase will have lost half its potential energy and will have only $9,8$ J left.

$$\begin{aligned} E_P &= mgh \\ &= (1\text{kg})(9,8\text{m} \cdot \text{s}^{-2})(1\text{m}) = 9,8 \text{ J} \end{aligned}$$

At the bottom of the cupboard the suitcase will have lost all its potential energy and its potential energy will be equal to zero.

$$\begin{aligned} E_P &= mgh \\ &= (1\text{kg})(9,8\text{m} \cdot \text{s}^{-2})(0\text{m}) = 0 \text{ J} \end{aligned}$$

This example shows us that objects have maximum potential energy at a maximum height and will lose their potential energy as they fall.

Example 1: *Gravitational potential energy*

QUESTION

A brick with a mass of 1 kg is lifted to the top of a 4 m high roof. It slips off the roof and falls to the ground. Calculate the gravitational potential energy of the brick at the top of the roof and on the ground once it has fallen.

SOLUTION

Step 1 : ***Analyse the question to determine what information is provided***

- The mass of the brick is $m = 1$ kg
- The height lifted is $h = 4$ m

All quantities are in SI units.

Step 2 : ***Analyse the question to determine what is being asked***

- We are asked to find the gain in potential energy of the brick as it is lifted
  onto the roof.
- We also need to calculate the potential energy once the brick is on the
  ground again.

Step 3 : ***Use the definition of gravitational potential energy to calculate the answer***

$$
\begin{aligned}
E_P &= mgh \\
&= (1\text{kg})(9,8\text{m} \cdot \text{s}^{-2})(4\text{m}) \\
&= 39,2 \text{ J}
\end{aligned}
$$

Example 2: More gravitational potential energy

QUESTION

A netball player, who is 1,7 m tall, holds a 0,5 kg netball 0,5 m above her head and shoots for the goal net which is 2,5 m above the ground. What is the gravitational potential energy of the ball:

1. *when she is about to shoot it into the net?*
2. *when it gets right into the net?*
3. *when it lands on the ground after the goal is scored?*

SOLUTION

Step 1 : ***Analyse the question to determine what information is provided***

- the netball net is 2,5 m above the ground
- the girl has a height of 1,7 m
- the ball is 0,5 m above the girl's head when she shoots for goal
- the mass of the ball is 0,5 kg

Step 2 : ***Analyse the question to determine what is being asked***

We need to find the gravitational potential energy of the netball at three different positions:

- when it is above the girl's head as she starts to throw it into the net
- when it reaches the net
- when it reaches the ground

Step 3 : ***Use the definition of gravitational potential energy to calculate the value for the ball when the girl shoots for goal***

$$E_P = mgh$$

First we need to calculate h. The height of the ball above the ground when the girl shoots for goal is h = (1,7 + 0,5) = 2,2 m.

Now we can use this information in the equation for gravitational potential energy:

$$\begin{aligned} E_P &= mgh \\ &= (0,5\text{kg})(9,8\text{m}\cdot\text{s}^{-2})(2,2\text{m}) \\ &= 10,78\text{ J} \end{aligned}$$

Step 4 : ***Calculate the potential energy of the ball at the height of the net***

Again we use the definition of gravitational potential energy to solve this:

$$\begin{aligned} E_P &= mgh \\ &= (0,5\text{kg})(9,8\text{m}\cdot\text{s}^{-2})(2,5\text{m}) \\ &= 12,25\text{ J} \end{aligned}$$

Step 5 : ***Calculate the potential energy of the ball on the ground***

$$\begin{aligned} E_P &= mgh \\ &= (0,5\text{kg})(9,8\text{m}\cdot\text{s}^{-2})(0\text{m}) \\ &= 0\text{ J} \end{aligned}$$

Exercise 22 - 1

1. Describe the relationship between an object's gravitational potential energy and its:
   a. mass and
   b. height above a reference point.
2. A boy, of mass 30 kg, climbs onto the roof of a garage. The roof is 2,5 m from the ground.

a. How much potential energy did the boy gain by climbing onto the roof?
b. The boy now jumps down. What is the potential energy of the boy when he is 1m from the ground?
c. What is the potential energy of the boy when he lands on the ground?

3. A hiker, of mass 70 kg, walks up a mountain, 800 m above sea level, to spend the night at the top in the first overnight hut. The second day she walks to the second overnight hut, 500 m above sea level. The third day she returns to her starting point, 200 m above sea level.
   a. What is the potential energy of the hiker at the first hut (relative to sea level)?
   b. How much potential energy has the hiker lost during the second day?
   c. How much potential energy did the hiker have when she started her journey (relative to sea level)?
   d. How much potential energy did the hiker have at the end of her journey when she reached her original starting position?

(1.) 00an (2.) 00ap (3.) 00aq

Kinetic energy

ESAHL

DEFINITION: Kinetic energy

Kinetic energy is the energy an object has due to its motion.
Quantity: Kinetic energy E_K Unit name: Joule Unit symbol: J

Kinetic energy is the energy an object has because of its motion. This means that any moving object has kinetic energy. Kinetic energy is defined as:

$$E_K = \frac{1}{2}mv^2$$

where E_K is the kinetic energy (measured in joules, J)

m = mass of the the object (measured in kg)

v = velocity of the object (measured in m $\cdot$ s^{-1}).

Tip

You may sometimes see kinetic energy written as KE. This is simply another way to write kinetic energy. We will not use this form in this book, but you may see it written like this in other books.

Therefore the kinetic energy E_K depends on the mass and velocity of an object. The faster it moves, and the more massive it is, the more kinetic energy it has. A truck of 2000 kg, moving at 100 km $\cdot$ hr^{-1} will have more kinetic energy than a car of 500 kg, also moving at 100 km $\cdot$ hr^{-1}.

Consider the 1 kg suitcase on the cupboard that was discussed earlier. When it is on the top of the cupboard, it will not have any kinetic energy because it is not moving:

$$\begin{aligned} E_K &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}(1 \text{ kg})(0 \text{ m} \cdot \text{s}^{-1})^2 = 0 \text{ J}. \end{aligned}$$

When the suitcase falls, its velocity increases (falls faster), until it reaches the ground with a maximum velocity. As its velocity velocity increases, it will gain kinetic energy. Its kinetic energy will increase until it is a maximum when the suitcase reaches the ground. If it has a velocity of 6,26 m $\cdot$ s^{-1} when it reaches the ground, its kinetic energy will be:

$$\begin{aligned} E_K &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}(1 \text{ kg})(6,26 \text{ m} \cdot \text{s}^{-1})^2 = 19,6 \text{ J}. \end{aligned}$$

Example 3: *Calculation of Kinetic Energy*

QUESTION

A 1 kg brick falls off a 4 m high roof. It reaches the ground with a velocity of 8,85 m · s^{-1}. What is the kinetic energy of the brick when it starts to fall and when it reaches the ground?

SOLUTION

Step 1 : ***Analyse the question to determine what information is provided***

- The mass of the brick m = 1 kg
- The velocity of the brick at the bottom v = 8,85 m · s^{-1}

These are both in the correct units so we do not have to worry about unit
conversions.

Step 2 : ***Analyse the question to determine what is being asked***

We are asked to find the kinetic energy of the brick at the top and the bottom. From the definition we know that to work out E_K, we need to know the mass and the velocity of the object and we are given both of these values.

Step 3 : ***Calculate the kinetic energy at the top***

Since the brick is not moving at the top, its kinetic energy is zero.

Step 4 : ***Substitute and calculate the kinetic energy***

$$\begin{aligned} E_K &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}(1 \text{ kg})(8,85 \text{ m} \cdot \text{s}^{-1})^2 \\ &= 39,2 \text{ J} \end{aligned}$$

Example 4: *Kinetic energy of 2 moving objects*

QUESTION

A herder is herding his sheep into the kraal. A mother sheep and its lamb are both running at 2,7 m · s^{-1} towards the kraal. The sheep has a mass of 80 kg and the lamb has a mass of 25 kg. Calculate the kinetic energy for each of the sheep and the lamb.

SOLUTION

Step 1 : ***Analyse the question to determine what information is provided***

- the mass of the mother sheep is 80 kg
- the mass of the lamb is 25 kg
- both the sheep and the lamb have a velocities of 2,7 m · s^{-1}

Step 2 : ***Analyse the question to determine what is being asked***

We need to find the kinetic energy of the sheep and the kinetic energy of its lamb

Step 3 : ***Use the definition to calculate the sheep's kinetic energy***

$$\begin{aligned} E_K &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}(80\ \text{kg})(2,7\ \text{m}\cdot\text{s}^{-1})^2 \\ &= 291,6\ \text{J} \end{aligned}$$

Step 4 : ***Use the definition to calculate the lamb's kinetic energy***

$$\begin{aligned} E_K &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}(25\ \text{kg})(2,7\ \text{m}\cdot\text{s}^{-1})^2 \\ &= 91,13\ \text{J} \end{aligned}$$

Note: Even though the sheep and the lamb are running at the same velocity, due to their different masses, they have different amounts of kinetic energy. The sheep has more than the lamb because it has a

higher mass.

Checking units

 ESAHM

According to the equation for kinetic energy, the unit should be $\text{kg} \cdot \text{m}^2 \cdot \text{s}^{-2}$. We can prove that this unit is equal to the joule, the unit for energy.

$$\begin{aligned}(\text{kg})\left(\text{m}\cdot\text{s}^{-1}\right)^2 &= \left(\text{kg}\cdot\text{m}\cdot\text{s}^{-2}\right)\cdot\text{m} \\ &= \text{N}\cdot\text{m} \quad \left(\text{because Force (N)} = \text{mass (kg)} \times \text{acceleration } \left(\text{m}\cdot\text{s}^{-2}\right)\right) \\ &= \text{J} \quad (\text{Work (J)} = \text{Force (N)} \times \text{distance (m)})\end{aligned}$$

We can do the same to prove that the unit for potential energy is equal to the joule:

$$\begin{aligned}(\text{kg})\left(\text{m}\cdot\text{s}^{-2}\right)(\text{m}) &= \text{N}\cdot\text{m} \\ &= \text{J}\end{aligned}$$

Example 5: *Mixing units & energy calculations*

QUESTION

A bullet, having a mass of 150 g, is shot with a muzzle velocity of 960 $m \cdot s^{-1}$. Calculate its kinetic energy.

SOLUTION

Step 1 : ***Analyse the question to determine what information is provided***

- We are given the mass of the bullet m = 150 g. This is not the unit we want mass to be in. We need to convert to kg.

$$\begin{aligned} \text{Mass in grams} \div 1000 &= \text{Mass in kg} \\ 150 \text{ g} \div 1000 &= 0,150 \text{ kg} \end{aligned}$$

- We are given the initial velocity with which the bullet leaves the barrel, called the muzzle velocity, and it is v = 960 m · s^{-1}.

Step 2 : ***Analyse the question to determine what is being asked***

- We are asked to find the kinetic energy.

Step 3 : ***Substitute and calculate***

We just substitute the mass and velocity (which are known) into the equation for kinetic energy:

$$\begin{aligned} E_K &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}(0,150 \text{ kg})(960 \text{ m} \cdot \text{s}^{-1})^2 \\ &= 69\,120 \text{ J} \end{aligned}$$

Exercise 22 - 2

1. Describe the relationship between an object's kinetic energy and its:
   a. mass and
   b. velocity
2. A stone with a mass of 100 g is thrown up into the air. It has an initial velocity of 3 m · s^{-1}. Calculate its kinetic energy:
   a. as it leaves the thrower's hand.
   b. when it reaches its turning point.
3. A car with a mass of 700 kg is travelling at a constant velocity of 100 km · hr^{-1}. Calculate the kinetic energy of the car.

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(1.) 00ar (2.) 00as (3.) 00at

Mechanical energy

ESAHN

DEFINITION: Mechanical energy

Mechanical energy is the sum of the gravitational potential energy and the kinetic energy of a system.
Quantity: Mechanical energy (E_M) Unit name: Joule Unit symbol: J

Mechanical energy, E_M, is simply the sum of gravitational potential energy (E_P) and the kinetic energy (E_K). Mechanical energy is defined as:

$$\boxed{E_M = E_P + E_K}$$

$$\boxed{E_M = mgh + \frac{1}{2}mv^2}$$

Tip

You may see mechanical energy written as U. We will not use this notation in this book, but you should be aware that this notation is sometimes used.

Example 6: Mechanical energy

QUESTION

Calculate the total mechanical energy for a ball of mass 0,15 kg which has a kinetic energy of 20 J and is 2 m above the ground.

SOLUTION

Step 1 : ***Analyse the question to determine what information is provided***

- The ball has a mass $m = 0,15$ kg
- The ball is at a height $h = 2$ m
- The ball has a kinetic energy $E_K = 20$ J

Step 2 : ***Analyse the question to determine what is being asked***

We need to find the total mechanical energy of the ball

Step 3 : ***Use the definition to calculate the total mechanical energy***

$$\begin{aligned} E_M &= E_P + E_K \\ &= mgh + \frac{1}{2}mv^2 \\ &= mgh + 20 \\ &= (0,15\,\text{kg})(9,8\,\text{m}\cdot\text{s}^{-1})(2\text{ m}) + 20\text{ J} \\ &= 2,94\text{ J} + 20\text{ J} \\ &= 22,94\text{ J} \end{aligned}$$

Conservation of mechanical energy

ESAHO

DEFINITION: Conservation of Energy

The Law of Conservation of Energy: Energy cannot be created or destroyed, but is merely changed from one form into another.

So far we have looked at two types of energy: gravitational potential energy and kinetic energy. The sum of the gravitational potential energy and kinetic energy is called the mechanical energy. In a closed system, one where there are no external dissipative forces acting, the mechanical energy will remain constant. In other words, it will not change (become more or less). This is called the Law of Conservation of Mechanical Energy.

Tip

In problems involving the use of conservation of energy, the path taken by the object can be ignored. The only important quantities are the object's velocity (which gives its kinetic energy) and height above the reference point (which gives its gravitational potential energy).

DEFINITION: Conservation of mechanical energy

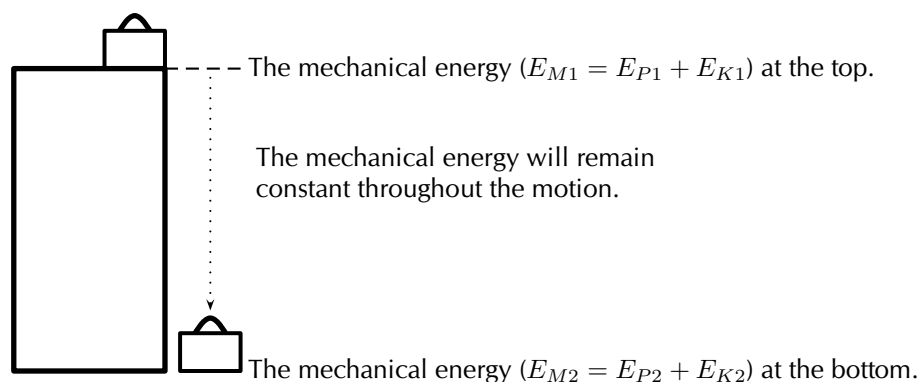
Law of Conservation of Mechanical Energy: The total amount of mechanical energy, in a closed system in the absence of dissipative forces (e.g. friction, air resistance), remains constant.

This means that potential energy can become kinetic energy, or vice versa, but energy cannot "disappear". For example, in the absence of air resistance, the mechanical energy of an object moving through the air in the Earth's gravitational field, remains constant (is conserved).

See simulation: (Simulation: VPgoo at www.everythingscience.co.za)

Using the law of conservation of energy ESAHP

Mechanical energy is conserved (in the absence of friction). Therefore we can say that the sum of the E_P and the E_K anywhere during the motion must be equal to the sum of the E_P and the E_K anywhere else in the motion.

We can now apply this to the example of the suitcase on the cupboard. Consider the mechanical energy of the suitcase at the top and at the bottom. We can say:

$$
\begin{aligned}
E_{M1} &= E_{M2} \\
E_{P1} + E_{K1} &= E_{P2} + E_{K2} \\
mgh + \frac{1}{2}mv^2 &= mgh + \frac{1}{2}mv^2 \\
(1\,\text{kg})(9,8\,\text{m}\cdot\text{s}^{-1})(2\text{ m}) + 0 &= 0 + \frac{1}{2}(1\,\text{kg})(v^2) \\
19,6 &= \frac{1}{2}(v^2) \\
v^2 &= 39,2\text{m}^2\cdot\text{s}^{-2} \\
v &= 6,26\text{ m}\cdot\text{s}^{-1}
\end{aligned}
$$

The suitcase will strike the ground with a velocity of $6,26\,\text{m}\cdot\text{s}^{-1}$.

From this we see that when an object is lifted, like the suitcase in our example, it gains potential energy. As it falls back to the ground, it will lose this potential energy, but gain kinetic energy. We know that energy cannot be created or destroyed, but only changed from one form into another. In our example, the potential energy that the suitcase loses is changed to kinetic energy.

The suitcase will have maximum potential energy at the top of the cupboard and maximum kinetic energy at the bottom of the cupboard. Halfway down it will have half kinetic energy and half potential energy. As it moves down, the potential energy will be converted (changed) into kinetic energy until all the potential energy is gone and only kinetic energy is left. The $19,6$ J of potential energy at the top will become $19,6$ J of kinetic energy at the bottom.

Activity:	*Conversion of energy*

Materials:

A length of plastic pipe with diameter approximately 20 mm, a marble, some masking tape and a measuring tape.

To do (1):

First put one end of the pipe on the table top so that it is parallel to the top of the table and tape it in position with the masking tape.

Lift the other end of the pipe upwards and hold it at a steady height not too high above the table.

Measure the vertical height from the table top to the top opening of the pipe.

Now put the marble at the top of the pipe and let it go so that it travels through the pipe and out the other end.

Questions:

- What is the velocity (i.e. fast, slow, not moving) of the marble when you first put it into the top of the pipe and what does this mean for its gravitational potential and kinetic energy?

- What is the velocity (i.e. fast, slow, not moving) of the marble when it reaches the other end of the pipe and rolls onto the desk? What does this mean for its gravitational potential and kinetic energy?

To do (2):
Now lift the top of the pipe as high as it will go.
Measure the vertical height of the top of the pipe above the table top.
Put the marble into the top opening and let it roll through the pipe onto the table.

Questions:

- What is the velocity (i.e. fast, slow, not moving) of the marble when you put it into the top of the pipe, and what does this mean for its gravitational potential and kinetic energy?
- Compared to the first attempt, what was different about the height of the top of the tube? How do you think this affects the gravitational potential energy of the marble?
- Compared to your first attempt, was the marble moving faster or slower when it came out of the bottom of the pipe the second time? What does this mean for the kinetic energy of the marble?

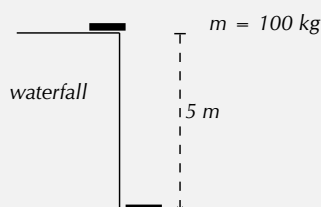
The activity with the marble rolling down the pipe shows very nicely the conversion between gravitational potential energy and kinetic energy. In the first instance, the pipe was held relatively low and therefore the gravitational potential energy was also relatively low. The kinetic energy at this point was zero since the marble wasn't moving yet. When the marble rolled out of the other end of the pipe, it was moving relatively slowly, and therefore its kinetic energy was also relatively low. At this point its gravitational potential energy was zero since it was at zero height above the table top.

In the second instance, the marble started off higher up and therefore its gravitational potential energy was higher. By the time it got to the bottom of the pipe, its gravitational potential energy was zero (zero height above the table) but its kinetic energy was high since it was moving much faster than the first time. Therefore, the gravitational potential energy was converted completely to kinetic energy (if we ignore friction with the pipe).

In the case of the pipe being held higher, the gravitational potential energy at the start was higher, and the kinetic energy (and velocity) of the marble was higher at the end. In other words, the total mechanical energy was higher and and only depended on the height you held the pipe above the table top and not on the distance the marble had to travel through the pipe.

Example 7: Using the Law of Conservation of Mechanical Energy

QUESTION

During a flood a tree trunk of mass 100 kg falls down a waterfall. The waterfall is 5 m high.

If air resistance is ignored, calculate:

1. *the potential energy of the tree trunk at the top of the waterfall.*
2. *the kinetic energy of the tree trunk at the bottom of the waterfall.*
3. *the magnitude of the velocity of the tree trunk at the bottom of the waterfall.*

SOLUTION

Step 1 : ***Analyse the question to determine what information is provided***

- The mass of the tree trunk $m = 100$ kg
- The height of the waterfall $h = 5$ m.
  These are all in SI units so we do not have to convert.

Step 2 : ***Analyse the question to determine what is being asked***

- Potential energy at the top
- Kinetic energy at the bottom
- Velocity at the bottom

Step 3 : ***Calculate the potential energy at the top of the waterfall.***

$$\begin{aligned} E_P &= mgh \\ &= (100\,\text{kg})(9,8\,\text{m}\cdot\text{s}^{-1})(5\text{ m}) \\ &= 4900\text{ J} \end{aligned}$$

Step 4 : ***Calculate the kinetic energy at the bottom of the waterfall.***

The total mechanical energy must be conserved.

$$E_{K1} + E_{P1} = E_{K2} + E_{P2}$$

Since the trunk's velocity is zero at the top of the waterfall, $E_{K1} = 0$.

At the bottom of the waterfall, $h = 0$ m, so $E_{P2} = 0$.

Therefore $E_{P1} = E_{K2}$ or in words:

The kinetic energy of the tree trunk at the bottom of the waterfall is equal to the potential energy it had at the top of the waterfall. Therefore E_K = 4900 J.

Step 5 : ***Calculate the velocity at the bottom of the waterfall.***

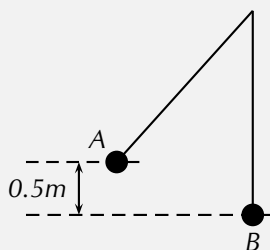
To calculate the velocity of the tree trunk we need to use the equation for kinetic energy.

$$\begin{aligned}
E_K &= \frac{1}{2}mv^2 \\
4900 &= \frac{1}{2}(100\,\text{kg})(v^2) \\
98 &= v^2 \\
v &= 9,899\ldots\,\text{m}\cdot\text{s}^{-1} \\
v &= 9,90\ \text{m}\cdot\text{s}^{-1}
\end{aligned}$$

Example 8: *Pendulum*

QUESTION

A 2 kg metal ball is suspended from a rope as a pendulum. If it is released from point A and swings down to the point B (the bottom of its arc):

1. *show that the velocity of the ball is independent of its mass,*
2. *calculate the velocity of the ball at point B.*

SOLUTION

Step 1 : ***Analyse the question to determine what information is provided***

- The mass of the metal ball is m = 2 kg
- The change in height going from point A to point B is h = 0,5 m
- The ball is released from point A so the velocity at point, v_A = 0 m · s^{-1}.

All quantities are in SI units.

Step 2 : ***Analyse the question to determine what is being asked***

- Prove that the velocity is independent of mass.
- Find the velocity of the metal ball at point B.

Step 3 : ***Apply the Law of Conservation of Mechanical Energy to the situation***

Since there is no friction, mechanical energy is conserved. Therefore:

$$\begin{aligned} E_{M1} &= E_{M2} \\ E_{P1} + E_{K1} &= E_{P2} + E_{K2} \\ mgh_1 + \frac{1}{2}m(v_1)^2 &= mgh_2 + \frac{1}{2}m(v_2)^2 \\ mgh_1 + 0 &= 0 + \frac{1}{2}m(v_2)^2 \\ mgh_1 &= \frac{1}{2}m(v_2)^2 \end{aligned}$$

The mass of the ball m appears on both sides of the equation so it can be eliminated so that the equation becomes:

$$\begin{aligned} gh_1 &= \frac{1}{2}(v_2)^2 \\ 2gh_1 &= (v_2)^2 \end{aligned}$$

This proves that the velocity of the ball is independent of its mass. It does not matter what its mass is, it will always have the same velocity when it falls through this height.

Step 4 : ***Calculate the velocity of the ball at point B***

We can use the equation above, or do the calculation from "first prin-

ciples":

$$
\begin{aligned}
(v_2)^2 &= 2gh_1 \\
(v_2)^2 &= (2)(9.8\,\text{m}\cdot\text{s}^{-1})(0,5\ \text{m}) \\
(v_2)^2 &= 9,8\,\text{m}\cdot\text{s}^{-1}\cdot\text{m} \\
v_2 &= \sqrt{9,8\ \text{m}^2\cdot\text{s}^{-2}} \\
v_2 &= 3,13\ \ \text{m}\cdot\text{s}^{-1}
\end{aligned}
$$

Alternatively you can do:

$$
\begin{aligned}
E_{K1} + E_{P1} &= E_{K2} + E_{P2} \\
mgh_1 + \frac{1}{2}m(v_1)^2 &= mgh_2 + \frac{1}{2}m(v_2)^2 \\
mgh_1 + 0 &= 0 + \frac{1}{2}m(v_2)^2 \\
(v_2)^2 &= \frac{2mgh_1}{m} \\
(v_2)^2 &= \frac{2(2\ \text{kg})(9,8\ \text{m}\cdot\text{s}^{-2})(0,5\ \text{m})}{2\ \text{kg}} \\
v_2 &= \sqrt{9,8\ \text{m}^2\cdot\text{s}^{-2}} \\
v_2 &= 3,13\ \ \text{m}\cdot\text{s}^{-1}
\end{aligned}
$$

Example 9: *The roller coaster*

QUESTION

A roller coaster ride at an amusement park starts from rest at a height of 50 m above the ground and rapidly drops down along its track. At some point, the track does a full 360 degree loop which has a height of 20 m, before finishing off at ground level. The roller coaster train itself with a full load of people on it has a mass of 850 kg.

Roller coaster

Photograph by Upsilon Andromedae on Flickr.com

If the roller coaster and its track are frictionless, calculate:

1. *the velocity of the roller coaster when it reaches the top of the loop*

2. *the velocity of the roller coaster at the bottom of the loop (i.e. ground level)*

SOLUTION

Step 1 : ***Analyse the question to determine what information is provided***

- The mass of the roller coaster is $m = 850$ kg
- The initial height of the roller coaster at its starting position is $h_1 = 50$ m
- The roller coaster starts from rest, so its initial velocity $v_1 = 0\text{m} \cdot \text{s}^{-1}$
- The height of the loop is $h_2 = 20$ m
- The height at the bottom of the loop is at ground level, $h_3 = 0$ m

We do not need to convert units as they are in the correct form already.

Step 2 : ***Analyse the question to determine what is being asked***

- the velocity of the roller coaster at the top of the loop
- the velocity of the roller coaster at the bottom of the loop

Step 3 : ***Calculate the velocity at the top of the loop***

From the conservation of mechanical energy, We know that at any two points in the system, the total mechanical energy must be the same. Let's compare the situation at the start of the roller coaster to the situation at the top of the loop:

$$\begin{aligned} E_{M1} &= E_{M2} \\ E_{K1} + E_{P1} &= E_{K2} + E_{P2} \\ 0 + mgh_1 &= \frac{1}{2}m(v_2)^2 + mgh_2 \end{aligned}$$

We can eliminate the mass, m, from the equation by dividing both sides by m.

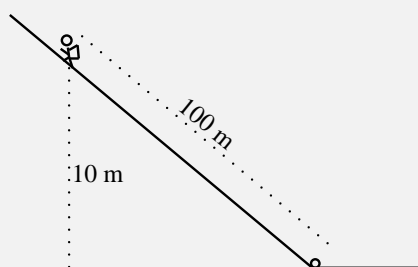
$$\begin{aligned} gh_1 &= \frac{1}{2}(v_2)^2 + gh_2 \\ (v_2)^2 &= 2(gh_1 - gh_2) \\ (v_2)^2 &= 2((9,8 \text{ m} \cdot \text{s}^{-2})(50 \text{ m}) - (9,8 \text{ m} \cdot \text{s}^{-2})(20 \text{ m})) \\ v_2 &= 24,25 \text{ m} \cdot \text{s}^{-1} \end{aligned}$$

Step 4 : ***Calculate the velocity at the bottom of the loop***

Again we can use the conservation of energy and the total mechanical energy at the bottom of the loop should be the same as the total mechanical energy of the system at any other position. Let's compare the situations at the start of the roller coaster's trip and the bottom of the loop:

$$\begin{aligned}
E_{M1} &= E_{M3} \\
E_{K1} + E_{P1} &= E_{K3} + E_{P3} \\
\frac{1}{2}m_1(0)^2 + mgh_1 &= \frac{1}{2}m(v_3)^2 + mg(0) \\
mgh_1 &= \frac{1}{2}m(v_3)^2 \\
(v_3)^2 &= 2gh_1 \\
(v_3)^2 &= 2(9,8\ \text{m}\cdot\text{s}^{-2})(50\ \text{m}) \\
v_3 &= 31,30\ \text{m}\cdot\text{s}^{-1}
\end{aligned}$$

Example 10: *An inclined plane*

QUESTION

A mountain climber who is climbing a mountain in the Drakensberg during winter, by mistake drops her water bottle which then slides 100 m down the side of a steep icy slope to a point which is 10 m lower than the climber's position. The mass of the climber is 60 kg and her water bottle has a mass of 500 g.

1. *If the bottle starts from rest, how fast is it travelling by the time it reaches the bottom of the slope? (Neglect friction.)*
2. *What is the total change in the climber's potential energy as she climbs down the mountain to fetch her fallen water bottle? i.e. what is the difference between her potential energy at the top of the slope and the bottom of the slope?*

SOLUTION

Step 1 : ***Analyse the question to determine what information is provided***

- the distance travelled by the water bottle down the slope, $d = 100$ m
- the difference in height between the starting position and the final position of the water bottle is $h = 10$ m
- the bottle starts sliding from rest, so its initial velocity $v_1 = 0$ m · s^{-1}
- the mass of the climber is 60 kg
- the mass of the water bottle is 500 g. We need to convert this mass into kg: 500 g = 0,5 kg

Step 2 : ***Analyse the question to determine what is being asked***

- What is the velocity of the water bottle at the bottom of the slope?
- What is the difference between the climber's potential energy when she is at the top of the slope compared to when she reaches the bottom?

Step 3 : ***Calculate the velocity of the water bottle when it reaches the bottom of the slope***

$$\begin{aligned}
E_{M1} &= E_{M2} \\
E_{K1} + E_{P1} &= E_{K2} + E_{P2} \\
\frac{1}{2}m(v_1)^2 + mgh_1 &= \frac{1}{2}m(v_2)^2 + mgh_2 \\
0 + mgh_1 &= \frac{1}{2}m(v_2)^2 + 0 \\
(v_2)^2 &= \frac{2mgh}{m} \\
(v_2)^2 &= 2gh \\
(v_2)^2 &= (2)(9,8\ \text{m}\cdot\text{s}^{-2})(10\ \text{m}) \\
v_2 &= 14\ \text{m}\cdot\text{s}^{-1}
\end{aligned}$$

Note: the distance that the bottle travelled (i.e. 100 m) does not play any role in calculating the energies. It is only the height difference that is important in calculating potential energy.

Step 4 : ***Calculate the difference between the climber's potential energy at the top of the slope and her potential energy at the bottom of the slope***

At the top of the slope, her potential energy is:

$$\begin{aligned}
E_{P1} &= mgh_1 \\
&= (60\,\text{kg})(9,8\,\text{m}\cdot\text{s}^{-1})(10\ \text{m}) \\
&= 5880\ \text{J}
\end{aligned}$$

At the bottom of the slope, her potential energy is:

$$\begin{aligned} E_{P2} &= mgh_1 \\ &= (60\,\text{kg})(9,8\,\text{m}\cdot\text{s}^{-1})(0) \\ &= 0\,\text{J} \end{aligned}$$

Therefore the difference in her potential energy when moving from the top of the slope to the bottom is:

$$E_{P1} - E_{P2} = 5880 - 0 = 5880\,\text{J}$$

Exercise 22 - 3

1. A tennis ball, of mass $120\,\text{g}$, is dropped from a height of $5\,\text{m}$. Ignore air friction.
   a. What is the potential energy of the ball when it has fallen $3\,\text{m}$?
   b. What is the velocity of the ball when it hits the ground?
2. A ball rolls down a hill which has a vertical height of 15 m. Ignoring friction, what would be the
   a. gravitational potential energy of the ball when it is at the top of the hill?
   b. velocity of the ball when it reaches the bottom of the hill?
3. A bullet, mass $50\,\text{g}$, is shot vertically up in the air with a muzzle velocity of $200\,\text{m}\cdot\text{s}^{-1}$. Use the Principle of Conservation of Mechanical Energy to determine the height that the bullet will reach. Ignore air friction.
4. A skier, mass $50\,\text{kg}$, is at the top of a $6,4\,\text{m}$ ski slope.
   a. Determine the maximum velocity that she can reach when she skis to the bottom of the slope.
   b. Do you think that she will reach this velocity? Why/Why not?
5. A pendulum bob of mass $1,5\,\text{kg}$, swings from a height A to the bottom of its arc at B. The velocity of the bob at B is $4\,\text{m}\cdot\text{s}^{-1}$. Calculate the height A from which the bob was released. Ignore the effects of air friction.

6. Prove that the velocity of an object, in free fall, in a closed system, is independent of its mass.

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Chapter 22 | Summary

See the summary presentation (Presentation: VPfvd at www.everythingscience.co.za)

- The gravitational potential energy of an object is the energy the object has because of its position in the gravitational field relative to some reference point.
- The kinetic energy of an object is the energy the object has due to its motion.
- The mechanical energy of an object is the sum of the potential energy and kinetic energy of the object.
- The unit for energy is the joule (J).
- The Law of Conservation of Energy states that energy cannot be created or destroyed, but can only be changed from one form into another.
- The Law of Conservation of Mechanical Energy states that the total mechanical energy of an isolated system (i.e. no friction or air resistance) remains constant.
- The table below summarises the most important equations:

Potential Energy	$E_P = mgh$
Kinetic Energy	$E_K = \frac{1}{2}mv^2$
Mechanical Energy	$E_M = E_K + E_P$

Physical Quantities		
Quantity	**Unit name**	**Unit symbol**
Potential energy (E_P)	joule	J
Kinetic energy (E_K)	joule	J
Mechanical energy (E_M)	joule	J

Table 22.1: Units used in **mechanical energy**

Chapter 22 End of chapter exercises

1. Give one word/term for the following descriptions.
   a. The force with which the Earth attracts a body.
   b. The unit for energy.
   c. The movement of a body in the Earth's gravitational field when no other forces act on it.

d. The sum of the potential and kinetic energy of a body.
  e. The amount of matter an object is made up of.

2. Consider the situation where an apple falls from a tree. Indicate whether the following statements regarding this situation are TRUE or FALSE. Write only "true" or "false". If the statement is false, write down the correct statement.

  a. The potential energy of the apple is a maximum when the apple lands on the ground.
  b. The kinetic energy remains constant throughout the motion.
  c. To calculate the potential energy of the apple we need the mass of the apple and the height of the tree.
  d. The mechanical energy is a maximum only at the beginning of the motion.
  e. The apple falls at an acceleration of $9,8\,\text{m} \cdot \text{s}^{-2}$.

3. A man fires a rock out of a slingshot directly upward. The rock has an initial velocity of $15\,\text{m} \cdot \text{s}^{-1}$.

  a. What is the maximum height that the rock will reach?
  b. Draw graphs to show how the potential energy, kinetic energy and mechanical energy of the rock changes as it moves to its highest point.

4. A metal ball of mass $200\,\text{g}$ is tied to a light string to make a pendulum. The ball is pulled to the side to a height (A), $10\,\text{cm}$ above the lowest point of the swing (B). Air friction and the mass of the string can be ignored. The ball is let go to swing freely.

  a. Calculate the potential energy of the ball at point A.
  b. Calculate the kinetic energy of the ball at point B.
  c. What is the maximum velocity that the ball will reach during its motion?

5. A truck of mass $1,2$ tons is parked at the top of a hill, $150\,\text{m}$ high. The truck driver lets the truck run freely down the hill to the bottom.

  a. What is the maximum velocity that the truck can achieve at the bottom of the hill?
  b. Will the truck achieve this velocity? Why/why not?

6. A stone is dropped from a window, $6\,\text{m}$ above the ground. The mass of the stone is $25\,\text{g}$. Use the Principle of Conservation of Energy to determine the speed with which the stone strikes the ground.

(1.) 00az (2.) 00b0 (3.) 00b1 (4.) 00b2 (5.) 00b3 (6.) 00b4

The hydrosphere 23

Introduction ESAHQ

As far as we know, the Earth we live on is the only planet that is able to support life. Amongst other factors, the Earth is just the right distance from the sun to have temperatures that are suitable for life to exist. Also, the Earth's atmosphere has exactly the right type of gases in the right amounts for life to survive. Our planet also has **water** on its surface, which is something very unique. In fact, Earth is often called the "Blue Planet" because most of it is covered in water. This water is made up of *freshwater* in rivers and lakes, the *saltwater* of the oceans and estuaries, *groundwater* and *water vapour*. Together, all these water bodies are called the **hydrosphere**.

The Earth

Photo by NASA on Flickr.com

See introductory video: (Video: VPbzp at www.everythingscience.co.za)

Interactions of the hydrosphere ESAHR

FACT

The total mass of the hydrosphere is approximately $1,4 \times 10^{18}$ tonnes! (The volume of one tonne of water is approximately 1 cubic meter (this is about 900 A4 textbooks!))

It is important to realise that the hydrosphere is not an isolated system, but rather interacts with other global systems, including the *atmosphere*, *lithosphere* and *biosphere*. These interactions are sometimes known collectively as the water cycle.

See video: VPbzy at www.everythingscience.co.za

- *Atmosphere* When water is heated (e.g. by energy from the sun), it evaporates and forms water vapour. When water vapour cools again, it condenses to form liquid water which eventually returns to the surface by precipitation e.g. rain or snow. This cycle of water moving through the atmosphere and the energy changes that accompany it, is what drives weather patterns on earth.
- *Lithosphere*
  In the lithosphere (the ocean and continental crust at the Earth's surface), water is an important *weathering* agent, which means that it helps to break rock down into rock fragments and then soil. These fragments may then be transported by water to another place, where they are deposited. These two processes (weathering and the

transporting of fragments) are collectively called *erosion*. Erosion helps to shape the earth's surface. For example, you can see this in rivers. In the upper streams, rocks are eroded and sediments are transported down the river and deposited on the wide flood plains lower down.

On a bigger scale, river valleys in mountains have been carved out by the action of water, and cliffs and caves on rocky beach coastlines are also the result of weathering and erosion by water. The processes of weathering and erosion also increase the content of dissolved minerals in the water. These dissolved minerals are important for the plants and animals that live in the water.

River valley

photo by AlanVernon on Flickr.com

- *Biosphere*

  In the biosphere, land plants absorb water through their roots and then transport this through their vascular (transport) system to stems and leaves. This water is needed in *photosynthesis*, the food production process in plants. Transpiration (evaporation of water from the leaf surface) then returns water back to the atmosphere.

Exploring the hydrosphere

ESAHS

The large amount of water on our planet is something quite unique. In fact, about 71% of the earth is covered by water. Of this, almost 97% is found in the oceans as saltwater, about $2,2\%$ occurs as a solid in ice sheets, while the remaining amount (less than 1%) is available as freshwater. So from a human perspective, despite the vast amount of water on the planet, only a very small amount is actually available for human consumption (e.g. drinking water).

In chapter 18 we looked at some of the reactions that occur in aqueous solution and saw some of the chemistry of water, in this section we are going to spend some time exploring a part of the hydrosphere in order to start appreciating what a complex and beautiful part of the world it is. After completing the following investigation, you should start to see just how important it is to know about the chemistry of water.

A lake

Photo by Duncan Brown (Cradlehall) on Flickr.com

Investigation: *Investigating the hydrosphere*

In groups of 3 - 4 choose one of the following as a study site: rock pool, lake, river, wetland or small pond. When choosing your study site, consider how accessible it is (how easy is it to get to?) and the problems you may experience (e.g. tides, rain).

Your teacher will provide you with the equipment you need to collect the following data. You can pick more than one study site and compare your data for each site.

- Measure and record data such as temperature, pH, conductivity and dissolved oxygen at each of your sites.
- Collect a water sample in a clear bottle, hold it to the light and see whether the water is clear or whether it has particles in it (i.e. what is the clarity of the water).
- What types of animals and plants are found in or near this part of the hydrosphere? Are they specially adapted to their environment?

Record your data in a table like the one shown below:

	Site 1	**Site 2**	**Site 3**
Temperature			
pH			
Conductivity			
Dissolved oxygen			
Clarity			
Animals			
Plants			

Interpreting the data Once you have collected and recorded your data, think about the following questions:

- How does the data you have collected vary at different sites?
- Can you explain these differences?
- What effect do you think *temperature*, *dissolved oxygen* and *pH* have on animals and plants that are living in the hydrosphere?
- Water is seldom “pure”. It usually has lots of things dissolved (e.g.

Mg^{2+}, Ca^{2+} and NO_3^- ions) or suspended (e.g. soil particles, debris) in it. Where do these substances come from?

- Are there any human activities near this part of the hydrosphere? What effect could these activities have on the hydrosphere?

The importance of the hydrosphere

It is so easy sometimes to take our hydrosphere for granted and we seldom take the time to really think about the role that this part of the planet plays in keeping us alive. Below are just some of the important functions of water in the hydrosphere:

- *Water is a part of living cells* Each cell in a living organism is made up of almost 75% water, and this allows the cell to function normally. In fact, most of the chemical reactions that occur in life, involve substances that are dissolved in water. Without water, cells would not be able to carry out their normal functions and life could not exist.
- *Water provides a habitat* The hydrosphere provides an important place for many animals and plants to live. Many gases (e.g. CO_2, O_2), nutrients e.g. nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+) ions, as well as other ions (e.g. Mg^{2+} and Ca^{2+}) are dissolved in water. The presence of these substances is critical for life to exist in water.
- *Regulating climate* One of water's unique characteristics is its high *specific heat*. This means that water takes a long time to heat up and also a long time to cool down. This is important in helping to regulate temperatures on earth so that they stay within a range that is acceptable for life to exist. *Ocean currents* also help to disperse heat.
- *Human needs* Humans use water in a number of ways. Drinking water is obviously very important, but water is also used domestically (e.g. washing and cleaning) and in industry. Water can also be used to generate electricity through hydropower.

These are just a few of the functions that water plays on our planet. Many of the functions of water relate to its chemistry and to the way in which it is able to dissolve substances in it.

Threats to the hydrosphere

It should be clear by now that the hydrosphere plays an extremely important role in the survival of life on Earth and that the unique properties of water allow various important chemical processes to take place which would otherwise not be possible. Unfortunately for us however, there are a number of factors that threaten our hydrosphere and most of these threats are because of human activities. We are going to focus on two of these issues: **pollution** and **overuse** and look at ways in which these problems can possibly be overcome.
See video: VPcbf at www.everythingscience.co.za

1. **Pollution**
   Pollution of the hydrosphere is a major problem. When we think of pollution, we sometimes only think of things like plastic, bottles, oil and so on. But any chemical that is present in the hydrosphere in an amount that is not what it should be is a pollutant. Animals and plants that live in the Earth's water bodies are specially adapted to surviving within a certain range of conditions. If these conditions are changed (e.g. through pollution), these organisms may not be able to survive. Pollution then, can affect entire aquatic ecosystems. The most common forms of pollution in the hydrosphere are *waste products* from humans and from industries, *nutrient pollution* e.g. fertiliser runoff which causes eutrophication (an excess of nutrients in the water leading to excessive plant growth) and toxic trace elements such as aluminium, mercury and copper to name a few. Most of these elements come from mines or from industries.
2. **Overuse of water**
   We mentioned earlier that only a very small percentage of the hydrosphere's water is available as freshwater. However, despite this, humans continue to use more and more water to the point where water *consumption* is fast approaching the amount of water that is *available*. The situation is a serious one, particularly in countries such as South Africa which are naturally dry and where water resources are limited. It is estimated that between 2020 and 2040, water supplies in South Africa will no longer be able to meet the growing demand for water in this country. This is partly due to population growth, but also because of the increasing needs of industries as they expand and develop. For each of us, this should be a very scary thought. Try to imagine a day without water... difficult isn't it? Water is so much a part of our lives, that we are hardly aware of the huge part that it plays in our daily lives.

As populations grow, so do the demands that are placed on dwindling water resources. While many people argue that building dams helps to solve this water-shortage problem, there is evidence that dams are only a temporary solution and that they often end up doing far more ecological damage than good. The only sustainable solution is to reduce the *demand* for water, so that water supplies are sufficient to meet this. The more important

question then is how to do this.

Group Discussion: Creative water conservation

Divide the class into groups, so that there are about five people in each. Each group is going to represent a different sector within society. Your teacher will tell you which sector you belong to from the following: farming, industry, city management, water conservation, tourism or civil society (i.e. you will represent the ordinary "man on the street"). In your groups, discuss the following questions as they relate to the group of people you represent: (Remember to take notes during your discussions and nominate a spokesperson to give feedback to the rest of the class on behalf of your group)

Dry landscape

Photo by flowcomm on Flickr.com

- What steps could be taken by your group to conserve water?
- Why do you think these steps are *not* being taken?
- What incentives do you think could be introduced to encourage this group to conserve water more efficiently?

Investigation: Building of dams

In the previous discussion, we mentioned that there is evidence that dams are only a temporary solution to the water crisis. In this investigation you will look at why dams are a potentially bad solution to the problem.
For this investigation you will choose a dam that has been built in your area, or an area close to you. Make a note of which rivers are in the area. Try to answer the following questions:

A dam

Photo by Redeo on Flickr.com

- If possible talk to people who have lived in the area for a long time and try to get their opinion on how life changed since the dam was built. If it is not possible to talk to people in the area, then look for relevant literature on the area.
- Try to find out if any environmental impact assessments (this is where people study the environment and see what effect the proposed project has on the environment) were done before the dam was built. Why do you think this is important?

- Look at how the ecology has changed. What was the ecology of the river before the dam was built? What is the current ecology? Do you think it has changed in a good way or a bad way? You could interview people in the community who lived there long ago before the dam was built.

Write a report or give a presentation in class on your findings from this investigation. Critically examine your findings and draw your own conclusion as to whether or not dams are only a short term solution to the growing water crisis.

It is important to realise that our hydrosphere exists in a delicate balance with other systems and that disturbing this balance can have serious consequences for life on this planet.

Project: **School Action Project**

There is a lot that can be done within a school to save water. As a class, discuss what actions could be taken by your class to make people more aware of how important it is to conserve water. Also consider what ways your school can save water. If possible, try to put some of these ideas into action and see if they really do conserve water. During break walk around the school and make a list of ll the places where water is being wasted.

How pure is our water?

ESAHV

When you drink a glass of water you are not just drinking water, but many other substances that are dissolved into the water. Some of these come from the process of making the water safe for humans to drink, while others come from the environment. Even if you took water from a mountain stream (which is often considered pure and bottled for people to consume), the water would still have impurities in it. Water pollution increases the amount of impurities in the water and sometimes makes the water unsafe for drinking. In this section we will look at a few of the substances that make water impure and how we can make pure water. We will also look at the pH of water.

In chapter 18 we saw how compounds can dissolve in water. Most of these compounds (e.g. Na^{+}, Cl^{-}, Ca^{2+}, Mg^{2+}, etc.) are safe for humans to consume in the small amounts that are naturally present in water. It is only when the amounts of these ions rise above the safe levels that the water is considered to be polluted.

You may have noticed sometimes that when you pour a glass a water straight from the tap, it has a sharp smell. This smell is the same smell that you notice around swimming pools and

is due to chlorine in the water. Chlorine is the most common compound added to water to make it safe for humans to use. Chlorine helps to remove bacteria and other biological contaminants in the water. Other methods to purify water include filtration (passing the water through a very fine mesh) and flocculation (a process of adding chemicals to the water to help remove small particles).

pH of water is also important. Water that is too basic (pH greater than 7) or too acidic (pH less than 7) may present problems when humans consume the water. If you have ever noticed after swimming that your eyes are red or your skin is itchy, then the pH of the swimming pool was probably too basic or too acidic. This shows you just how sensitive we are to the smallest changes in our environment. The pH of water depends on what ions are dissolved in the water. Adding chlorine to water often lowers the pH. You will learn more about pH in grade 11.

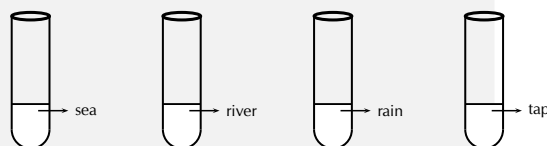
General experiment: *Water purity*

Aim: To test the purity and pH of water samples

Apparatus:
pH test strips (you can find these at pet shops, they are used to test pH of fish tanks), microscope (or magnifying glass), filter paper, funnel, silver nitrate, concentrated nitric acid, barium chloride, acid, chlorine water (a solution of chlorine in water), carbon tetrachloride, some test-tubes or beakers, water samples from different sources (e.g. a river, a dam, the sea, tap water, etc.).

Method:

1. Look at each water sample and note if the water is clear or cloudy.
2. Examine each water sample under a microscope and note what you see.
3. Test the pH of each of the water samples.
4. Pour some of the water from each sample through filter paper.
5. Refer to chapter 18 for the details of common anion tests. Test for chloride, sulphate, carbonate, bromide and iodide in each of the water samples.

Results: Write down what you saw when you just looked at the water samples. Write down what you saw when you looked at the water samples under a microscope. Where there any dissolved particles? Or other things in the water? Was there a difference in what you saw with just looking and with looking with a microscope?

Write down the pH of each water sample. Look at the filter paper from each sample. Is there sand or other particles on it? Which anions did you find in each sample?

Discussion: Write a report on what you observed. Draw some conclusions on the purity of the water and how you can tell if water is pure or not.

Conclusion: You should have seen that water is not pure, but rather has many substances dissolved in it.

Project: **Water purification**

Prepare a presentation on how water is purified. This can take the form of a poster, or a presentation or a written report. Things that you should look at are:

- Water for drinking (potable water)
- Distilled water and its uses
- Deionised water and its uses
- What methods are used to prepare water for various uses
- What regulations govern drinking water
- Why water needs to be purified
- How safe are the purification methods

Chapter 23 | Summary

See the summary presentation (Presentation: VPfbj at www.everythingscience.co.za)

- The **hydrosphere** includes all the water that is on Earth. Sources of water include freshwater (e.g. rivers, lakes), saltwater (e.g. oceans), groundwater (e.g. boreholes) and water vapour. Ice (e.g. glaciers) is also part of the hydrosphere.
- The hydrosphere interacts with other **global systems**, including the atmosphere, lithosphere and biosphere.
- The hydrosphere has a number of important **functions**. Water is a part of all living cells, it provides a habitat for many living organisms, it helps to regulate climate and it is used by humans for domestic, industrial and other use.
- Despite the importance of the hydrosphere, a number of factors threaten it. These include **overuse** of water, and **pollution**.
- Water is not pure, but has many substances dissolved in it.

Chapter 23 End of chapter exercises

1. What is the hydrosphere? How does it interact with other global systems?

2. Why is the hydrosphere important?

3. Write a one page essay on the importance of water and what can be done to ensure that we still have drinkable water in 50 years time.

More practice video solutions or help at www.everythingscience.co.za

(1.) 00b5 (2.) 00b6 (3.) 024v

Units used in the book 24

Quantities used in the book ESAHW

Physical Quantities		
Quantity	**Unit name**	**Unit symbol**
Amplitude (A)	metre	m
Atomic mass unit (amu)	u	u
Average acceleration ($\vec{a}_{av}$)	metre per second squared	m · s^{-2}
Average speed (v_{av})	metre	m
Average velocity ($\vec{v}_{av}$)	metre per second	m · s^{-1}
Charge (Q)	coulomb	C
Concentration (C)	mol per decimetre cubed	$mol \cdot dm^{-3}$
Current (I)	ampere	A
Density (d)	grams per centimetre cubed	$g \cdot cm^{-3}$
Displacement (Δx)	metre	m
Distance (D)	metre	m
Energy (E)	Joule	J
Frequency (f)	Hertz	Hz
Instantaneous acceleration ($\vec{a}$)	metre per second squared	m · s^{-2}
Instantaneous speed (v_{av})	metre per second	m · s^{-1}
Instantaneous velocity ($\vec{v}$)	metre per second	m · s^{-1}
Intensity (I)	deciBel	dB
Magnitude of acceleration (a)	metre per second squared	m · s^{-2}
Mass (m)	gram	g
Molar mass (M)	gram per mol	$g \cdot mol^{-1}$
Mole (n)	mole	mol

Table 24.1: Units used in **the book**

Physical Quantities		
Quantity	**Unit name**	**Unit symbol**
Period (T)	second	s
Position (x)	metre	m
Potential difference (V)	Volt	V
Pulse speed (v)	metre per second	$\text{m} \cdot \text{s}^{-1}$
Resistance (R)	Ohm	Ω
Temperature (T)	degrees	$\circ$
Volume (V)	decimetre cubed	dm^{-3}
Wavelength (λ)	metre	m
Wavespeed (v)	metre per second	$\text{m} \cdot \text{s}^{-1}$

Table 24.2: Units used in **the book**

Exercise solutions 25

Science skills

ESAHX

Exercise 1-1

ESAHY

1. (a) $3,63 \times 10^{6}$
   (b) $37,83$
   (c) $6,3 \times 10^{-4}$
2. (a) $5,11 \times 10^{5}$ V
   (b) $1,0 \times 10^{-1}\ell$
   (c) 5×10^{-7} m
   (d) $2,50 \times 10^{-7}$ m
   (e) $3,5 \times 10^{-2}$ g
3. (a) $0,1602$ aC
   (b) $1,992$ MJ
   (c) $59,8$ kN
   (d) $2,5$ mA
   (e) $7,5$ km

Exercise 1-2

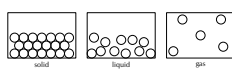
ESAHZ

1. (a) $1,01 \times 10^{4}$ Pa
   (b) $9,8 \times 10^{2}$ m · s^{-2}
   (c) $1,256 \times 10^{-6}$ A
2. (a) microgram and -6
   (b) milligram and -3
   (c) kilogram and 3
   (d) megagram and 6
3. (a) $1,23 \times 10^{-6}$ N
   (b) $4,17 \times 10^{8}$ kg
   (c) $2,47 \times 10^{5}$ A
   (d) $8,80 \times 10^{-4}$ mm
4. (a) $1,01\mu$s
   (b) 1 000 mg
   (c) $7,2$ Mm
   (d) 11 nℓ
5. $234,44$ m · s^{-1}
6. 373 K

Classification of matter

ESAIA

End of chapter exercises

ESAIB

1. a
2. a
3. (a) compound
   (b) compound
   (c) heterogeneous mixture
   (d) solution
   (e) solution
   (f) compound
   (g) element
   (h) solution
4. (a) D
   (b) A
   (c) E
   (d) B
   (e) C
5. (a) use a magnet
   (b) magnetism
6. (a) Ag
   (b) KBr
   (c) CO_2
7. (a) sodium bromide
   (b) barium sulphate
   (c) sulphur dioxide
   (d) sulphuric acid
8. (a) $FeSO_4$
   (b) BF_3
   (c) $KMnO_4$
   (d) $ZnCl_2$
9. (a) friction
   (b) durable
   (c) durable
   (d) shiny
   (e) easily moulded
   (f) fibrous

States of matter and the KMT

ESAIC

End of chapter exercises

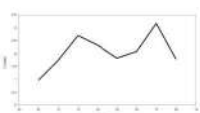
ESAID

1. (a) sublimation
   (b) evaporation
2. (a) see definition
   (b) liquid to gas
3. see definition
4. (a) solid, solid, gas, solid, gas, solid
   (b) carbon
   (c) helium
5. solid liquid gas

The atom

ESAIE

End of chapter exercises

ESAIF

1. (a) atomic mass number
   (b) electron orbital
2. (a) false
   (b) true
   (c) true
   (d) false
3. B
4. B
5. A
6. C
7. B
8. (a) ${}^{5}_{4}$Be
   (b) ${}^{12}_{6}$C
   (c) ${}^{48}_{22}$Ti
   (d) ${}^{19}_{9}$F
9. (a) [Ne]$3s^{2}3p^{1}$
   (b) [Ne]$3s^{2}3p^{3}$
   (c) [He]$2s^{2}2p^{2}$
   (d) [He]$2s^{2}2p^{6}$
   (e) [Ne]$3s^{2}3p^{6}$
10. (a) $78; 117; 78$
    (b) $18; 22; 18$
    (c) $27; 32; 27$
    (d) $3; 4; 3$
    (e) $5; 6; 5$
11. (a) Rh
    (b) 17
    (c) 9
12. B
13. $63, 62$ u

The periodic table

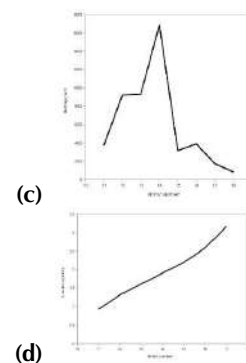
ESAIG

End of chapter exercises

ESAIH

1. (a) false
   (b) true
   (c) false
   (d) false
2. (a) first ionisation energy
   (b) period
   (c) halogens
3. (a) Br > Cl
   (b) Cl > Br
   (c) Cl > Br
   (d) Br > Cl
4. (a)
   (b)

   (c)

   (d)

Chemical bonding

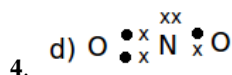
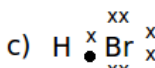
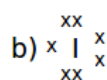
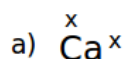
ESAII

End of chapter exercises

ESAIJ

2. B

3. B

4.
a) Ca x x
b) x I x x xx xx
c) H x• Br x x xx xx
d) O •• x x N •• x O xx

5. (a) 1
   (b) 3
   (c) hydrogen and nitrogen

6.

	K^+	Ca^{2+}	NH_4^+
OH^-	KOH	$Ca(OH)_2$	NH_4OH
O^{2-}	K_2O	CaO	$(NH_4)_2O$
NO_3^-	KNO_3	$Ca(NO_3)_2$	NH_4NO_3
PO_4^{3-}	K_3PO_4	$Ca_3(PO_4)_2$	$(NH_4)_3PO_4$

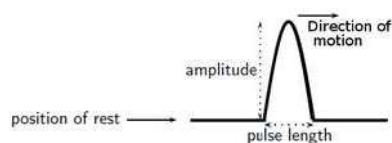
7. (a) potassium (K^+) dichromate ($Cr_2O_7^{2-}$)
   (b) $K_2Cr_2O_7$

Transverse pulses

ESAIK

End of chapter exercises

ESAIL

1.

2. 15 m

3. $0,3 \text{ m} \cdot \text{s}^{-1}$

4. $0,05 \text{ s}$

Transverse waves ESAIM

End of chapter exercises ESAIN

1. (a) $0,2$ m
   (b) $1,33$ s
2. (a) 3
   (b) (i) BD
   (ii) AB
   (iii) BD
   (c) $0,75$ m
   (d) $0,625$ s
   (e) $1,60$ Hz
   (f) $14,4$ m · s^{-1}

Longitudinal waves ESAIO

End of chapter exercises ESAIP

1. A
2. D
3. a. 10 m
   b. 2 m · s^{-1}
4. a. $\frac{1}{256}$ s
   b. $1,25$ m

Sound ESAIQ

End of chapter exercises ESAIR

1. (a) frequency
   (b) amplitude
   (c) waveform
2. E
3. D
4. C
5. C
6. B
7. E
8. C
9. A
10. C
11. B
12. A
13. C
14. $1\ 700$ m
15. $0,15$ s
16.
17. radios
18. $25,8$ m
19. $0,57$ m 600 Hz
20. increase wavelength
21. 17 mm

22. $34,4$ m
23. $1\,812,5$ mm
24. 172 m
25. (a) sound waves
    (b) transverse waves
    (c) wavelength
    (d) frequency
    (e) amplitude
    (f) wave speed
    (g) wave speed
    (h) period

EM radiation

ESAIS

End of chapter exercises

ESAIT

1. 2.0×10^{-25} J
2. 3×10^{-19} J
3. $8,6 \times 10^{-21}$ J
4. $3,0 \times 10^{3}$ m
5. For the photon with wavelength 532 nm: E $= 3,7 \times 10^{-19}$ J
   For the photon with frequency 13 Hz: E $= 8,6 \times 10^{-24}$ J
   The energy of the second photon is: $2,3 \times 10{-}2$ m.
6. Radio, microwave, infrared, visible, ultraviolet, X-ray, gamma ray

The particles that substances are made of

ESAIU

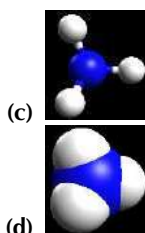
End of chapter exercises

ESAIV

1. (a) molecule
   (b) empirical formula
   (c)
   (d)

(3) (a) covalent
    (b) NH_3

(4) (a) covalent molecular
    (b) metallic network
    (c) covalent network
    (d) covalent molecular
    (e) ionic network

(5) (a) carbon dioxide
    (b) CO_2
    (c) covalent

Physical and chemical change ESAIW

End of chapter exercises ESAIX

(1) (a) physical change
(b) chemical change
(c) synthesis reaction
(2) see definitions
(3) (a) physical change
(b) chemical change
(c) chemical change
(d) chemical change
(e) physical change
(f) physical change
(g) physical change
(h) chemical change
(4) (a) decomposition
(b) synthesis
(c) decomposition

Representing chemical change ESAIY

End of chapter exercises ESAIZ

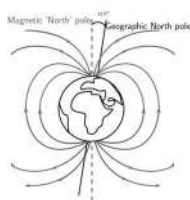
(1) $C_3H_8(\ell) + 5O_2(g) \rightarrow 3CO_2(g) + H_2O(\ell)$
(2) $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
(3) (a) P_4 (s) + $5O_2$ (g) → $2P_2O_5$ (s)
(b) same number of atoms on both sides
(c) phosphorus oxide
(d) synthesis
(4) $2C_2H_6$ (g) + $7O_2$ (g) → $4CO_2$ (g) + $6H_2O(\ell)$
(5) $2N_2O_5 \rightarrow 4NO_2 + O_2$
(6) $2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O$ $2H_2S + SO_2 \rightarrow 3S + 2H_2O$
(7) $C_{14}H_{18}N_2O_5$ (s) + $16O_2$ (g) → $9H_2O(\ell)$ + $14CO_2$ (g) + N_2 (g)

Magnetism ESAJA

End of chapter exercises ESAJB

(4) Each piece will have a N and S pole
(5) they repel
(6) they attract

(11) the aurora

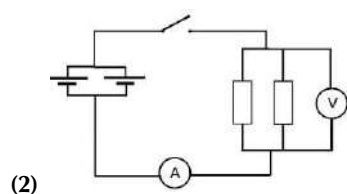
(12)

Electrostatics ESAJC

End of chapter exercises ESAJD

(1) positive and negative
(2) rubbing two objects together
(3) repulsive, attractive
(4)
  (a) repulsive
  (b) increase by factor of 4
(5) D
(8) B
(9) polarisation
(12) 60 electrons
(13) -376×10^{-17} C
(14) 376×10^{-17} C
(15) $7,28 \times 10^{-18}$ C, 45 electrons
(16) same as at start
(17) neutral, 0 electrons

Electric circuits ESAJE

End of chapter exercises ESAJF

(2)

(4) 1
(5) d
(6)
  (a) brighter
  (b) A and B are the same, C is off
  (c) B
(7) a
(8) $4,25$ V
(9) 17 V
(10) 7 V
(11) $1,4$ V
(12) 18Ω
(13) $7,5\Omega$
(14) 15 V
(15) 2 V

Reactions in aqueous solutions

ESAJG

End of chapter exercises

ESAJH

(1)
- **(a)** condensation
- **(b)** ion
- **(c)** hardness
- **(d)** sulphur trioxide
- **(e)** C
- **(f)** B
- **(g)** I

(2)
- **(a)** B
- **(b)** H
- **(c)** E
- **(d)** A

(5)
- **(a)** molecular
- **(b)** ionic
- **(c)** molecular
- **(d)** molecular
- **(e)** ionic
- **(f)** ionic

(6)
- **(a)** X: carbonate, Y: sulphate, Z: chloride
- **(b)** $CO_3^{2-} + Ba^{2+} + Cl^- \rightarrow BaCO_3 + Cl^-$

Quantitative aspects of chemical change

ESAJI

End of chapter exercises

ESAJJ

(1)
- **(a)** molar mass
- **(b)** Avogadro's number

(2) D

(3) A

(4) A

(5) C

(6)
- **(a)** $0,31$
- **(b)** $0,09$
- **(c)** $0,04$
- **(d)** $5,06$

(7)
- **(a)** $11,2$
- **(b)** $21,62$
- **(c)** $20,8$
- **(d)** $6,72$
- **(e)** $145,66$

(8)
- **(a)** Cl: $31,49$ C: $64,02$ H: $4,48$
- **(b)** Li: $29,17$ O: $66,67$ H: $4,17$

(9) CF_2Cl_2

(10) NO_2

(11) I_4O_9

(12)
- **(a)** C_2H_4F
- **(b)** $C_4H_8F_2$

(13) 5

(14)
- **(b)** $0,03$
- **(c)** yes

(15)
- **(a)** 4
- **(b)** incorrect
- **(c)** $0,1$mols

(16)
- **(a)** $196,14$
- **(b)** $292,32$
- **(c)** $94,1$

(17) $11,098$

Vectors

ESAJK

End of chapter exercises

ESAJL

(1) B
(2) D
(3) A
(4) A

Motion in one dimension

ESAJM

End of chapter exercises

ESAJN

(1)
- (a) displacement
- (b) vector
- (c) acceleration
- (d) reference point
- (e) velocity
- (f) instantaneous velocity

(2)
- (a) displacement
- (b) acceleration
- (c) velocity
- (d) velocity

(3)
- (a) false
- (b) true
- (c) true
- (d) false

(4) B
(5) D
(6) A
(7) C

(8)
- (a) $30\text{ m}\cdot\text{ s}^{-1}$
- (b) $7,5\text{ m}\cdot\text{ s}^{-2}$
- (c) 8 s
- (d) 300 m

(9) D
(10) A

(11)
- (a) $-1,75\text{ m}\cdot\text{ s}^{-2}$
- (b) $4,8\text{ s}$

(12)
- (a) 72 s
- (b) $27,8\text{ m}\cdot\text{ s}^{-1}$
- (c) $100\text{ km}\cdot\text{ h}^{-1}$

(13)
- (a) $0,6\text{ m}\cdot\text{ s}^{-1}$ $1,5\text{ m}$ $-0,4\text{ m}\cdot\text{ s}^{-2}$
- (b) $11,5\text{ s}$

(14)
- (a) $1,11\text{ m}\cdot\text{ s}^{-1}$
- (b) $1,8\text{ s}$
- (c) $16,67\text{ m}\cdot\text{ s}^{-1}$
- (d) 30 m
- (e) determines safe distance
- (f) no
- (g) 60 m

(15)
- (a) 35 s
- (b) $15,71\text{ m}\cdot\text{s}^{-1}$

Mechanical energy

ESAJO

End of chapter exercises

ESAJP

(1) **(a)** Gravitational force
(b) joules
(c) free fall
(d) mechanical energy
(e) mass

(2) **(a)** false
(b) false
(c) true
(d) false
(e) true

(3) **(a)** $11,48$ m

(4) **(a)** $0,196$ J
(b) $0,196$ J
(c) $1,4$ m · s^{-1}

(5) **(a)** $54,22$ m · s^{-1}
(b) no

(6) $7,7$ m · s^{-1}

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